TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

MAY TO DECEMBER, 1913

VOL. XXXII, PART II

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N. Y., U. S. A.
1913

Copyright, 1913
by the
American Institute of Electrical Engineers

Press of Mellroy & Emmet, 22 Thames Street, New York

OFFICERS AND BOARD OF DIRECTORS

1912-1913

PRESIDENT.

RALPH D. MERSHON.

JUNIOR PAST-PRESIDENTS.

DUGALD C. JACKSON. GANO DUNN.

VICE-PRESIDENTS.

DAVID B. RUSHMORE.
W. G. CARLTON.
CHARLES W. STONE.
A. W. BERRESFORD.
WILLIAM S. MURRAY.
SEVERN D. SPRONG.

MANAGERS.

H. H. BARNES, JR.
R. G. BLACK.
W. S. RUGG.
CHARLES E. SCRIBNER.
F. S. HUNTING.
NORMAN W. STORER.
WILLIAM S. LEE.
PARLEY OSGOOD.
COMFORT A. ADAMS.
J. FRANKLIN STEVENS.
WILLIAM B. JACKSON.
WILLIAM McCLELLAN.

TREASURER.

GEORGE A. HAMILTON.

SECRETARY.

F. L. HUTCHINSON.

HONORARY SECRETARY.

RALPH W. POPE,
33 West 39th Street, New York.

GENERAL COUNSEL.

PARKER and AARON,
52 Broadway, New York

PAST-PRESIDENTS.—1884-1912.

*NORVIN GREEN, 1884-5-6.
*FRANKLIN L. POPE, 1886-7.
T. COMMERFORD MARTIN, 1887-8.
EDWARD WESTON, 1889-9.
ELIHU THOMSON, 1889-90.
*WILLIAM A. ANTHONY, 1890-91.
ALEXANDER GRAHAM BELL, 1891-2.
FRANK JULIAN SPRAGUE, 1892-3.
EDWIN J. HOUSTON, 1893-4-5.
LOUIS DUNCAN, 1895-6-7.
FRANCIS BACON CROCKER, 1897-8.
A. E. KENNELLY, 1898-1900.
CARL HERING, 1900-1.
CHARLES P. STEINMETZ, 1901-2.
CHARLES F. SCOTT, 1902-3.
BION J. ARNOLD, 1903-4.
JOHN W. LIEB, JR., 1904-5.
SCHUYLER SKAATS WHEELER, 1905-6.
SAMUEL SHELDON, 1906-7.
HENRY G. STOTT, 1907-8.
LOUIS A. FERGUSON, 1908-09.
LEWIS B. STILLWELL, 1909-10.
DUGALD C. JACKSON, 1910-11.
GANO DUNN, 1911-12.

*Deceased.

LOCAL HONORARY SECRETARIES.

JAMES S. FITZMAURICE,
G. P. O. Perth, Australia.
HORACE FIELD PARSHALL,
Salisbury House, London Wall, E. C., London.
L. A. HERDT, McGill University, Montreal Que.
CLARE P. BEAMES,
Bangalore, Mysore Province, India.
WILLIAM G. T. GOODMAN,
Adelaide, South Australia.
ROBERT JULIAN SCOTT,
Christ Church, New Zealand.
HENRY GRAFTIO, St. Petersburg, Russia.
RICHARD O. HEINRICH,
Genest-str. 5 Schoeneberg, Berlin, Germany
A. S. GARFIELD, 67 Avenue de Malakoff, Paris, France.

STANDING COMMITTEES

EXECUTIVE COMMITTEE.

RALPH D. MERSHON, Chairman.
COMFORT A. ADAMS. WILLIAM S. MURRAY.
GEORGE A. HAMILTON. W. S. RUGG.
CHARLES W. STONE.

Finance Committee.
CHARLES W. STONE, Chairman.
A. W. BERRESFORD.
W. S. RUGG.

Code Committee.
PARLEY OSGOOD, Chairman.
J. C. FORSYTHE.
H. B. GEAR.
H. N. MULLER.
A. M. SCHOEN.
GEORGE F. SEVER.
JOHN B. TAYLOR.

Meetings and Papers Committee.
W. S. RUGG, Chairman.
H. W. BUCK.
A. F. GANZ.
W. C. L. EGLIN.
JOHN M. HIPPLE.
H. A. HORNOR.
S. G. McMEEN.
H. H. NORRIS.
E. W. RICE, Jr.
F. J. SPRAGUE.
H. G. STOTT.
PERCY H. THOMAS.
JOHN B. WHITEHEAD.
GEORGE R. WOOD.

Library Committee.
SAMUEL SHELDON, Chairman.
FREDERICK BEDELL.
PHILANDER BETTS.
DUGALD C. JACKSON.
MALCOLM Mac LAREN.

Editing Committee.
LEWIS T. ROBINSON, Chairman.
ALBERT F. GANZ.
CARY T. HUTCHINSON.
A. S. McALLISTER.
WALTER I. SLICHTER.
NORMAN W. STORER.

Law Committee.
CHARLES A. TERRY, Chairman
CLIFTON V. EDWARDS.
FRANCIS BLOSSOM.
W. G. CARLTON.
GEORGE E. CRUSE.

Board of Examiners.
PERCY H. THOMAS, Chairman.
MAURICE COSTER.
A. F. GANZ.
A. S. McALLISTER
WILLIAM McCLELLAN

Standards Committee.
A. E. KENNELLY, Chairman.
COMFORT A. ADAMS. Secretary
W. C. L. EGLIN.
H. W. FISHER.
E. R. HILL.
PETER JUNKERSFELD.
B. G. LAMME.
W. L. MERRILL.
W. S. MOODY.
W. H. POWELL.
CHARLES ROBBINS.
CHARLES F. SCOTT.
J. FRANKLIN STEVENS.
CHARLES P. STEINMETZ.
SAMUEL W. STRATTON.

Sections Committee.
PAUL M. LINCOLN, Chairman.
H. W. CROZIER.
S. G. McMEEN.
GEORGE F. SEVER.
J. FRANKLIN STEVENS.

Chairman of Sections. Ex-officio Members.
A. M. SCHOEN.
J. B. WHITEHEAD.
F. P. VALENTINE.
RALPH H. RICE.
E. J. EDWARDS.
T. W. BEHAN.
O. S. MORE.
E. L. NICHOLS.
G. A. DAMON.
W. A. HALL.
E. H. KIFER.
H. S. POLEY.
T. E. BARNUM.
A. L. ABBOTT.
H. A. HORNOR.
E. L. FARRAR.
W. C. SMITH.
H. R. WAKEMAN.
H. W. CROZIER.
JOHN B. TAYLOR.
J. D. ROSS.
JOSEPH A. OSBORN.
JOHN B. FISKEN.
GEORGE E. KIRK.
P. A. GABY.
A. M. BUCK.
F. D. NIMS.
JOHN H. FINNEY.

SPECIAL COMMITTEES

Railway Committee.
FRANK J. SPRAGUE, Chairman.
A. H. BABCOCK.
FRED. DARLINGTON
C. E. EVELETH
GEORGE GIBBS.
CARY T. HUTCHINSON.
DUGALD C. JACKSON.
EDWIN B. KATTE.
RICHARD McCULLOCH.
WILLIAM S. MURRAY.
LEWIS B. STILLWELL.
B. F. WOOD.

Telegraphy and Telephony Committee.
S. G. McMEEN, Chairman.
P. F. FOWLE.
H. M. FRIENDLY.
BANCROFT GHERARDI.
A. H. GRISWOLD.
F. J. HAYER.
H. MOURADIAN.
L. M. POTTS.
HENRY L. REBER.
ALLARD SMITH.
J. L. WAYNE.
GEORGE J. YUNDT.

High Tension Transmission Committee.
PERCY H. THOMAS, Chairman.
H. E. BUSSEY.
MAX COLLBOHM.
G. FACCIOLI.
P. T. HANSCOM.
JOHN HARISBERGER.
R. F. HAYWARD.
HAROLD PENDER.
NORMAN ROWE.
C. S. RUFFNER.
DAVID B. RUSHMORE.
HARRIS J. RYAN.
P. W. SOTHMAN.

Electric Lighting Committee.
W. C. L. EGLIN, Chairman.
R. G. BLACK.
K. H. HANSEN.
SIDNEY HOSMER.
PETER JUNKERSFELD.
J. A. LIGHTHIPE.
S. J. LISBERGER.
H. W. PECK.
T. S. PERKINS.
D. W. ROPER.
L. E. SINCLAIR.
W. F. WELLS.

Industrial Power Committee.
JOHN M. HIPPLE, Chairman.
H. B. EMERSON.
R. S. FEICHT.
E. FRIEDLANDER.
E. H. KIFER.
C. D. KNIGHT.
J. C. LINCOLN.
R. S. MASSOL.
W. H. POWELL.
BARTON R. SHOVER.
R. H. TILLMAN.

Educational Committee.
HENRY H. NORRIS, Chairman.
C. R. DOOLEY.
W. A. HILLEBRAND.
JOHN PRICE JACKSON.
G. W. LAMKE.
C. L. MEES.
A. J. ROWLAND.
ROBERT SIBLEY.
WALTER I. SLICHTER.
CHARLES P. STEINMETZ.

SPECIAL COMMITTEES—Continued

Electrochemical Committee.
ALBERT F. GANZ, Chairman.
E. R. BERRY.
CHARLES E. BONINE.
C. F. BURGESS.
C. P. ELWELL.
A. McK. GIFFORD.
CARL HERING.
W. R. WITHNEY.

Power Station Committee.
HENRY G. STOTT, Chairman.
C. L. DEMURALT.
GLENDOWER DUNBAR.
J. H. HANNA.
HENRY A. LARDNER.
H. ST. CLAIR PUTNAM.
SEVERN D. SPRONG.
F. A. VAUGHIN.
W. F. WELLS.

Committee on Use of Electricity in Mines.
GEORGE R. WOOD, Chairman.
C. W. BIERS.
H. H. CLARK.
C. T. HENDERSON.
W. E. MOORE.
A. J. NICHT.
K. A. PAULY.
W. A. THOMAS.
H. M. WARREN.

Electrophysics Committee.
JOHN B. WHITEHEAD, Chairman.
L. W. CHUBB.
W. S. FRANKLIN.
EDWARD P. HYDE.
CARL KINSLEY.
EDWARD L. NICHOLS.
E. F. NORTHRUP.
G. W. PIERCE.
M. I. PUPIN.
EDWARD B. ROSA.
HARRIS J. RYAN.
H. CLYDE SNOOK.
CHARLES P. STEINMETZ

Committee on the Use of Electricity in Marine Work.
H. A. HORNOR, Chairman.
FRANK R. BACON.
J. J. CRAIN.
MAXWELL W. DAY.
W. L. R. EMMET.
F. C. HANKER.
O. P. LOOMIS.
C. S. McDOWELL.
DAVID M. MAHOOD.
J. P. MALLETT.
JULIUS MARTIN.
ELMER A. SPERRY.

Public Policy Committee.
CALVERT TOWNLEY, Chairman.
JOHN J. CARTY.
C. C. CHESNEY.
JOHN H. FINNEY.
HENRY FLOY.
W. W. FREEMAN.
C. F. LACOMBE.
L. A. OSBORNE.
E. W. RICE, Jr.

Code of Principles of Professional Conduct.
B. A. BEHREND, Chairman.
JOHN F. KELLY.
H. ST. CLAIR PUTNAM.
LEWIS T. ROBINSON.
GEORGE F. SEVER.

Patent Committee.
BION J. ARNOLD, Chairman.
C. S. BRADLEY.
F. F. FOWLE.
PETER COOPER HEWITT.
JOHN F. KELLY.
H. WARD LEONARD.
M. I. PUPIN.
W. E. WINSHIP.
B. F. WOOD.

Committee on Sections Participation in Conduct of Institute Affairs.
E. A. BALDWIN, Chairman.
DUGALD C. JACKSON.
W. S. LEE.
PAUL M. LINCOLN.
S. G. McMEEN.
CHARLES F. SCOTT.
CHARLES P. STEINMETZ.
PERCY H. THOMAS.

Relations of Consulting Engineers.
LEWIS B. STILLWELL, Chairman.
FRANCIS BLOSSOM.
W. K. DUNLAP.
FRANK R. FORD.
E. W. RICE, Jr.
FRANK J. SPRAGUE.

Membership Committee.
H. CLYDE SNOOK, Chairman.
E. A. BALDWIN.
F. J. BULLIVANT.
S. K. COLBY.
MAURICE COSTER.
HENRY FLOY.
ROBERT T. LOZIER.
C. E. MAGNUSSON.
K. C. RANDALL.
E. P. ROBERTS.
A. M. SCHOEN.
C. E. SCRIBNER.

INTERNATIONAL ELECTRICAL CONGRESS, SAN FRANCISCO, 1915.

Executive Committee of Committee on Organization.
CHARLES P. STEINMETZ, President.
CHARLES F. SCOTT, First Vice-President.
A. E. KENNELLY, Vice-President on Program.
C. O. MAILLOUX, Vice-President on International Relations.
HENRY A. LARDNER, Vice President on Pacific Coast Relations.
EDWARD B. ROSA, Secretary.
PRESTON S. MILLAR, Treasurer and Business Manager.

Historical Museum Committee.
T. C. MARTIN, Chairman.
JOHN J. CARTY.
CHARLES L. CLARKE.
LOUIS DUNCAN.
E. W. RICE, Jr.
CHARLES F. SCOTT.
FRANK J. SPRAGUE.

Index Transactions Committee.
GEORGE I. RHODES.

International Electrotechnical Commission.

United States National Committee.
C. O. MAILLOUX, President.
A. E. KENNELLY, Secretary
COMFORT A. ADAMS.
B. A. BEHREND.
LOUIS BELL.
FRANCIS B. CROCKER.
GANO DUNN.
W. C. L. EGLIN.
H. W. FISHER.
BANCROFT GHERARDI.
JOHN W. HOWELL.
PETER JUNKERSFELD.
B. G. LAMME.
W. S. MOODY.
EDWARD B. ROSA.
CHARLES F. SCOTT.
SAMUEL SHELDON.
C. E. SKINNER.
CHARLES P. STEINMETZ.

Constitutional Revision Committee.
WILLIAM S. MURRAY, Chairman.
W. G. CARLTON.
F. L. HUTCHINSON.
DUGALD C. JACKSON.
PAUL M. LINCOLN.
H. ST. CLAIR PUTNAM.
LEWIS T. ROBINSON.
CHARLES F. SCOTT.
CHARLES E. SKINNER.
LEWIS B. STILLWELL.
CHARLES W. STONE.
HENRY G. STOTT.
JOHN B. TAYLOR.
PERCY H. THOMAS.
CALVERT TOWNLEY.

New York Reception Committee.
A. H. LAWTON, Chairman.
H. H. BARNES, Jr.
F. C. BATES.
H. M. BRINCKERHOFF.
W. G. CARLTON.
MAURICE COSTER.
H. W. FLASHMAN.
HENRY FLOY.
J. W. LIEB, Jr.
R. T. LOZIER.
O. S. LYFORD, Jr.
C. O. MAILLOUX.
WILLIAM McCLELLAN.
W. E. McCOY.
F. A. MUSCHENHEIM.
FARLEY OSGOOD.
C. E. SCRIBNER.
GEORGE F. SEVER.
SAMUEL SHELDON.
S. D. SPRONG.
P. H. THOMAS.
CALVERT TOWNLEY.
W. F. WELLS.

SPECIAL COMMITTEES—Continued

Special Committee on Organization of Technical Committees.

H. G. STOTT, Chairman.
COMFORT A. ADAMS.
H. W. BUCK.
P. M. LINCOLN.
H. S. PUTNAM.

Joubert Memorial Committee.

C. O. MAILLOUX, Chairman.
COMFORT A. ADAMS.
CARL HERING.
C. E. SCRIBNER.
W. D. WEAVER.

Edison Medal Committee.

Appointed by the President for terms of five years.

Term expires July 31, 1917.
A. E. KENNELLY.
H. WARD LEONARD.
ROBERT T. LOZIER.

Term expires July 31, 1916.
FRANK J. SPRAGUE.
SCHUYLER S. WHEELER.
W. D. WEAVER.

Term expires July 31, 1915.
ELIHU THOMSON, Chairman.
JOHN W. LIEB, Jr.
EDWARD L. NICHOLS.

Term expires July 31, 1914.
PHILIP P. BARTON.
JOHN J. CARTY.
JAMES G. WHITE.

Term expires July 31, 1913.
COMFORT A. ADAMS.
C. C. CHESNEY.
RICHARD N. DYER.

Elected by the Board of Directors from its own membership for terms of two years.

Term expires July 31, 1914.
FARLEY OSGOOD.
W. S. RUGG.
CHARLES E. SCRIBNER.

Term expires July 31, 1913.
LEWIS B. STILLWELL.
H. H. BARNES, Jr.
SEVERN D. SPRONG.

Ex-Officio Members.
RALPH D. MERSHON, President.
GEO. A. HAMILTON, Treasurer.
F. L. HUTCHINSON, Secretary.

Sections and their Secretaries

ATLANTA
H. M. Keys,
So. Bell Tel. & Tel. Co., Atlanta, Ga.

BALTIMORE
L. M. Potts,
Industrial Building, Baltimore, Md.

BOSTON
Leavitt L. Edgar,
39 Boylston St., Boston, Mass.

CHICAGO
E. W. Allen,
1028 Monadnock Building, Chicago, Ill.

CLEVELAND
R. E. Scovel,
American Steel and Wire Company, Cleveland, Ohio.

DETROIT ANN ARBOR
Ray K. Holland,
Cornwall Building, Ann Arbor, Mich.

FORT WAYNE
P. H. Haselton,
Fort Wayne Electric Works, Ft. Wayne, Ind.

INDIANAPOLIS-LAFAYETTE
Charles A. Tripp,
710 Majestic Building, Indianapolis, Ind

ITHACA
George S. Macomber,
Cornell University, Ithaca, N. Y.

LOS ANGELES
E. R. Northmore,
Los Angeles G. & E. Co., Los Angeles, Cal.

LYNN
E. R. Berry,
General Electric Co., Lynn, Mass.

MADISON
F. A. Kartak,
Univ. of Wisconsin, Madison, Wis.

MEXICO
James Carson,
Mexican L. & P. Co., Mexico City, Mexico

MILWAUKEE
L. P. Reinhard,
Mech. Appliance Co., Milwaukee, Wis.

MINNESOTA
Fred G. Dustin,
9 South Fifth St., Minneapolis, Minn

PHILADELPHIA
H. F. Sanville,
1326 Chestnut St., Philadelphia, Pa.

PITTSBURGH
M. C. Turpin,
Dept. of Publicity, W. E. and M. Company, Pittsburgh, Pa.

PITTSFIELD
W. W. Lewis,
General Electric Co., Pittsfield, Mass.

PORTLAND, ORE.
G. P. Nock,
Pacific Tel. and Tel. Co. Portland, Ore.

SAN FRANCISCO
A. G. Jones,
819 Rialto Bldg, San Francisco, Cal.

SCHENECTADY
J. A. Dewhurst,
Gen. Elec. Co., Schenectady, N. Y.

SEATTLE
M. T. Crawford,
608 Electric Bldg., Seattle, Wash.

ST. LOUIS
A. McR. Harrelson,
Emerson Elec. Mfg. Co., St. Louis, Mo.

TOLEDO
Max Neuber,
Care of Cohen, Freidlander & Martin, Toledo, O.

SPOKANE
H. B. Peirce,
Box 1436, Spokane, Wash

TORONTO
H. T. Case,
Continental Life Bldg., Toronto, Ont.

URBANA
F. G. Wilson,
Univ. of Illinois, Urbana, Ill.

VANCOUVER
L. G. Robinson,
British Columbia Elec. Railway Company, Vancouver, B. C.

WASHINGTON, D. C.
C. B. Mirick,
1330 New York Ave., N. W., Washington, D. C.

Branches and their Secretaries

AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS
E. S. Lammers, Jr.,
College Station, Texas.

ARKANSAS, UNIV. OF
G. W. Watkins,
Room 26, Buchanan Hall,
Fayetteville Ark.

ARMOUR INSTITUTE
T. C. Bolton,
Armour Inst. Tech.,
Chicago, Ill.

BUCKNELL UNIVERSITY
Robert L. Rooke,
Bucknell University,
Lewisburg, Pa.

CALIFORNIA, UNIV. OF
L. E. Rushton,
University of California,
Berkeley, Cal.

CINCINNATI, UNIV. OF
A. H. Davis,
Univ. of Cincinnati,
Cincinnati, O.

CLEMSON AGRICULTURAL COLLEGE
H. J. Bomar,
Clemson College, S. C.

COLORADO STATE AGRICULTURAL COLLEGE
R. K. Havighorst,
Colorado State Agricultural College,
Fort Collins, Colo.

COLORADO, UNIV. OF
Frank A. Redding,
Univ. of Colorado,
Boulder, Colo.

HIGHLAND PARK COL.
Ralph R. Chatterton,
Highland Park College,
Des Moines, Iowa.

IOWA STATE COLLEGE
F. A. Robbins,
Iowa State College,
Ames, Iowa.

IOWA, UNIV. OF
A. H. Ford,
Univ. of Iowa,
Iowa City, Ia.

KANSAS STATE AGR. COL.
W. C. Lane,
Kansas State Agric. Col.,
Manhattan, Kan.

KANSAS, UNIV. OF
A. J. Pecht,
Univ. of Kansas,
Lawrence, Can.

KENTUCKY, STATE UNIV. OF
W. M. Lane,
216 Rose Street,
Lexington, Ky.

LAFAYETTE COLLEGE
V. A. Davison,
Lafayette College,
Easton, Pa.

LEHIGH UNIVERSITY
E. P. Weaver,
Lehigh University,
S. Bethlehem, Pa.

LEWIS INSTITUTE
A. H. Fensholt,
Lewis Institute,
Chicago, Ill.

MAINE, UNIV. OF
J. Larcom Ober,
S. A. E. House,
Orono, Maine.

MICHIGAN, UNIV. OF
Edward A. Roeser,
Univ. of Michigan,
Ann Arbor, Mich.

MISSOURI, UNIV. OF
E. W. Kellogg,
9 Engineering Building,
Columbia, Mo.

MONTANA STATE COL.
J. A. Thaler,
Montana State College,
Bozeman, Mont.

NEBRASKA, UNIV. OF
V. L. Hollister,
Station A,
Lincoln, Nebraska.

NEW HAMPSHIRE COL.
Clayton W. Work,
New Hampshire College,
Durham, N. H.

NORTH CAROLINA COL. OF AGR. AND MECH. ARTS
J. W. Johnson,
N. C. Col. of A. and M. Arts
West Raleigh, N.C.

OHIO NORTHERN UNIV.
D. W. Yambert,
Ohio Northern Univ.,
Ada, Ohio.

OHIO STATE UNIV.
T. O. Farmer,
Ohio State Univ.,
Columbus, Ohio.

OKLAHOMA AGRICULTURAL AND MECH. COL.
J. W. Harvey,
416 Hester Street,
Stillwater, Okla.

OKLAHOMA, UNIV. OF
Leo H. Gorton,
526 Univ. Boulevard,
Norman, Okla.

OREGON AGR. COL.
Charles E. Oakes,
Oregon Agric. Col.,
Corvallis, Ore.

OREGON, UNIV. OF
C. R. Reid,
Univ. of Oregon,
Eugene, Oregon.

PENN STATE COLLEGE
I. S. Nippes,
Pennsylvania State Col.,
State College, Pa.

PURDUE UNIV.
A. N. Topping,
Purdue University,
Lafayette, Ind.

RENSSELAER POLY. INST.
W. J. Williams,
Rensselaer Poly. Inst.,
Troy, N. Y.

ROSE POLY. INST.
Joseph E. O'Connell,
457 N. 8th Street,
Terre Haute, Ind.

RHODE ISLAND STATE COLL.
L. A. Whittaker.

STANFORD UNIV.
L. M. Bussert,
Stanford University,
California.

SYRACUSE UNIV.
R. A. Porter,
Syracuse University,
Syracuse, N. Y.

TEXAS, UNIV. OF
Joseph W. Ramsey,
University of Texas,
Austin, Tex.

THROOP COLLEGE OF TECHNOLOGY
R. W. Parkinson,
Throop Poly. Institute,
Pasadena, Cal.

UNIV. OF WASHINGTON
S. R. Shave,
Univ. of Washington,
Seattle, Wash.

VERMONT, UNIV. OF
O. Krupp,
65 North Bend St.,
Burlington, Vt.

VIRGINIA, UNIV. OF
Henry Woodman Clark,
A. X. P. House,
University, Virginia.

WASH., STATE COL. OF
H. V. Carpenter,
State Col. of Wash.,
Pullman, Wash.

WASHINGTON UNIV.
A. S. Blatterman,
45 Lewis Place,
St. Louis, Mo.

WORCESTER POLY. INST.
George I. Gilchrest,
Worcester Poly. Inst.,
Worcester, Mass.

YALE UNIVERSITY
M. R. Wibberley,
136 Vanderbilt-Scientific,
New Haven, Conn.

INSTITUTE REPRESENTATIVES

On Board of Award, John Fritz Medal.

LEWIS B. STILLWELL. GANO DUNN.
DUGALD C. JACKSON. RALPH D. MERSHON.

On Board of Trustees, United Engineering Society.

H. H. BARNES, Jr. GANO DUNN.
CHARLES E. SCRIBNER.

On Library Board of United Engineering Society.

SAMUEL SHELDON. DUGALD C. JACKSON.
FREDERICK BEDELL. MALCOLM MACLAREN.
F. L. HUTCHINSON.

On Resuscitation Commission.

A. E. KENNELLY. ELIHU THOMSON.

On Electrical Committee of National Fire Protection Association.

The Chairman of the Institute's Code Committee, FARLEY OSGOOD.

On Advisory Board of American Year-Book.

EDWARD CALDWELL.

On Advisory Board, National Conservation Congress.

CALVERT TOWNLEY.

On Council of American Association for the Advancement of Science.

W. S. FRANKLIN. G. W. PIERCE.

On Conference Committee of National Engineering Societies.

CALVERT TOWNLEY. W. W. FREEMAN.

On Joint Committee on Engineering Education.

CHARLES F. SCOTT. SAMUEL SHELDON.

On American Electric Railway Association's Committee on Joint Use of Poles.

FARLEY OSGOOD. F. B. H. PAINE.
PERCY H. THOMAS.

On National Joint Committee on Electrolysis.

BION J. ARNOLD. F. N. WATERMAN.
PAUL WINSOR.

On Board of Managers, Panama-Pacific International Engineering Congress, 1915.

A. M. HUNT. J. G. DeREMER.
And the PRESIDENT and SECRETARY of the Institute.

CONTENTS.

MEETING AT NEW YORK, JANUARY 10, 1913.

High-Speed Turbo-Alternators—Designs and Limitations—By B. G. Lamme. (*Illustrated*) 1

MEETING AT NEW YORK, FEBRUARY 26-28, 1913.

Temperature and Electrical Insulation—By C. P. Steinmetz and B. G. Lamme. (*Illustrated.*) 79

Method of Rating Electrical Apparatus.—By W. L. Merrill, W. H. Powell and Charles Robbins. (*Illustrated*) 91

Notes on Internal Heating of Stator Coils—By R. B. Williamson. (*Illustrated.*) 153

Measurement of Temperature in Rotating Electric Machines—By L. W. Chubb, E. I. Chute and O. W. A. Oetting. (*Illustrated.*) 163

Method of Determining Temperature of Alternating-Current Generators and Motors and Room Temperature—By Henry G. Reist and T. S. Eden. (*Illustrated.*) 177

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines—By J. A. Capp and L. T. Robinson 185

Methods of Determining Temperature of Transformers and of Cooling Medium—By S. E. Johannesen and G. W. Wade. (*Illustrated.*) 191

Methods of Determining Temperature of Transformers—By W. M. McConahey and C. Fortescue. (*Illustrated.*) 213

Correction of Transformer Temperatures for Variation in Room Temperature, Taking Into Account Both Copper and Iron Losses—By C. Fortescue 227

The Temperature Rise of Stationary Induction Apparatus as Influenced by the Effects of Temperature, Barometric Pressure and Humidity of the Cooling Medium—By J. J. Frank and W. O. Dwyer. (*Illustrated.*) 235

Effect of Room Temperature on Temperature Rise of Motors and Generators—By Maxwell W. Day and R. A. Beekman. (*Illustrated.*) 259

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electric Apparatus—By C. E. Skinner, L. W. Chubb and Phillips Thomas. (*Illustrated.*) 279

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions—By C. B. Blanchard and C. T. Anderson. (*Illustrated.*) 289

Laws of Heat Transmission in Electrical Machinery—By Irving Langmuir 301

Current Rating of Electric Cables.—By Ralph W. Atkinson and H. W. Fisher 325

The Rating of Cables Carrying Current—By Saul Dushman. (*Illustrated.*) 333
The Myriawatt—By H. G. Stott and Haylett O'Neill 411
Induction Motor Load Losses—By Henry G. Reist and A. E. Averrett. (*Illustrated.*) 423
Stray Losses in Induction Motors.—By A. M. Dudley. (*Illustrated*) 429
Notes on Induction Motor Losses—By R. W. Davis 435
Losses in Transformers—By W. W. Lewis. (*Illustrated.*) 439
Stray Losses in Transformers—By C. Fortescue and W. M. McConahey. (*Illustrated.*) 465
Determination of Load Loss Correction Factors for Rotating Electric Machines—By E. M. Olin and S. L. Henderson. (*Illustrated.*) . 479
Load Losses of Alternating-Current Generators—By W. J. Foster and Edgar Knowlton. (*Illustrated.*) 503
Notes on Stray Losses in Synchronous Machines—By F. K. Brainard 519
Stray Loss in Direct-Current Commutating Machines—By H. F. T. Erben and H. S. Page. (*Illustrated.*) 523
The Determination of Stray Losses from Input-Output Tests—By L. T. Robinson. (*Illustrated.*) 531
Sources of Error in the Efficiency Determination of Rotating Electric Machines—By Elmer I. Chute and William Bradshaw. (*Illustrated.*) 551
Brush Friction and Contact Losses—By H. F. T. Erben and A. H. Freeman. (*Illustrated.*) 559
Methods of Determining Brush Losses Due to Contact and Friction—By H. R. Edgecomb and W. A. Dick. (*Illustrated.*) 565
Commutation and Brush Loss.—By C. E. Wilson. (*Illustrated.*) 577
Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Tests—By P. D. Newbury. (*Illustrated.*) 649
Comparison of Methods of Making Load Tests on A-C. Generators and on Induction Motors—By E. F. Collins and W. E. Holcombe 667
Notes on Methods of Making Load Tests on Large Induction Motors—By A. M. Dudley. (*Illustrated.*) 683
Load Tests on Transformers—By J. J. K. Madden. (*Illustrated.*) . . 691
Sources of Error in Transformer Tests—By W. M. McConahey and C. Fortescue 703
Rating of Oil Circuit Breakers with Reference to Rupturing Capacity—By George A. Burnham 731
The Sphere Spark Gap.—By S. W. Farnsworth and C. L. Fortescue. (*Illustrated.*) 733
Calibration of the Sphere Gap Voltmeter—By L. W. Chubb and C. Fortescue. (*Illustrated*) 739
Potential Waves of Alternating-Current Generators—By W. J. Foster. (*Illustrated.*) 749
Wave Form Distortions and Their Effects on Electrical Apparatus—By P. M. Lincoln. (*Illustrated.*) 765
A Proposed Wave Shape Standard—By Cassius M. Davis. (*Illustrated.*) 775
The Experimental Determination of the Regulation of Alternators—By A. B. Field. (*Illustrated.*) 783
Regulation of Definite Pole Alternators—By Soren H. Mortensen. (*Illustrated.*) 789
Generator and Prime Mover Capacities—By David B. Rushmore and Eric A. Lof. (*Illustrated.*) 795

MEETING AT SAN FRANCISCO, FEBRUARY 28, 1913.

Operation of Transmission Lines—By Lee Hagood. (*Illustrated.*) . . 855

MEETING AT NEW YORK, MARCH 14, 1913.

Air as an Insulator When in the Presence of Insulating Bodies of Higher Specific Inductive Capacity—By C. L. Fortescue and S. W. Farnsworth (*Illustrated.*) 893
The Application of a Theorem of Electrostatics to Insulation Problems—By C. Fortescue. (*Illustrated.*) 907

MEETINGS AT NEW YORK, MARCH 19, 26, APRIL 2, 9, 16, 1913.

Radioactivity—By Edwin Plimpton Adams. (*Illustrated.*) 953

MEETING AT PITTSBURGH, APRIL 18-19, 1913.

Purchased Power in Coal Mines—By H. C. Eddy 1029
Central Station Power for Coal Mines—By C. W. Beers 1035
Safeguarding the Use of Electricity in Mines—By H. H. Clark 1055
Alternating-Current Motors for the Economic Operation of Mine Fans—By F. B. Crosby. (*Illustrated.*) 1073
Central Station Power for Mines—By J. S. Jenks 1097
Characteristics of Substation Loads at the Anthracite Collieries of the Lackawanna R. R. Co—By H. M. Warren and A. S. Biesecker. (*Illustrated.*) 1103
Mining Loads for Central Stations—By Wilfred Sykes and Graham Bright. (*Illustrated.*) 1121

CONTENTS.

MEETING AT NEW YORK, MAY 20, 1913.

2400-Volt Railway Electrification.—By H. M. Hobart 1149
Trunk Line Electrification.—By Charles P. Kahler 1189

MEETING AT COOPERSTOWN, JUNE 24-27, 1913.

Some Aspects of Institute Affairs.—President's Address.—By Ralph D. Mershon 1261
A Suggestion for the Engineering Profession.—By William McClellan 1271
Test of an Artificial Aerial Telephone Line at a Frequency of 750 Cycles per Second.—By A.E. Kennelly and F.W. Lieberknecht (*Illustrated*) 1283
Automatic Methods in Long Distance Telephone Operation.—By H. M. Friendly and A. E. Burns. (*Illustrated*) 1305
Electrolytic Corrosion of Iron in Soils.—By Burton McCollum and K. H. Logan. (*Illustrated*) 1345
The National Association of Corporation Schools.—By F. C. Henderschott 1413
Vocational Education in Philadelphia and Vicinity.—By A. J. Rowland 1417
The Pennsylvania Railroad Company Apprentice Schools.—By John Price Jackson and J. W. L. Hale 1437
Suggested Specifications for Testing High Voltage Suspension Insulators.—By F. W. Peek, Jr 1457
Suggested Specifications for Testing High-Voltage Insulators.—By J. A. Sandford, Jr 1462
Insulator Testing Specification for Insulators having an Operating Voltage Exceeding 25,000 Volts.—By Percy H. Thomas 1471
The Behavior of Synchronous Motors During Starting.—By F. D. Newbury. (*Illustrated*) 1509
Commutating-Pole Saturation in D-C Machines.—By Harold E. Stokes. (*Illustrated*) 1527
Constant Voltage Transmission.—By H. B. Dwight. (*Illustrated*) 1545
The Industrial Use of Synchronous Motors by Central Stations.—By John C. Parker. (*Illustrated*) 1559
Theory of the Non-Elastic and Elastic Catenary as Applied to Transmission Lines.—By C. A. Pierce, F. J. Adams and G. I. Gilchrest. (*Illustrated*) 1565
Electrical Requirements of Certain Machines in the Rubber Industry.—By C. A. Kelsey. (*Illustrated*) 1583
Standardization of Method for Determining and Comparing Power Costs in Steam Plants.—By H. G. Stott and W. S. Gorsuch. (*Illustrated*) 1619
Automatic Substations.—By H. R. Summerhayes. (*Illustrated*) 1685
Converting Substations in Basements and Sub-Basements.—By B. G. Jamieson. (*Illustrated*) 1699
Operation of Frequency Changers.—By N. E. Funk. (*Illustrated*) 1713
The Electric Strength of Air—IV.—By J. B. Whitehead and T. T. Fitch. (*Illustrated.*) 1737
The Positive and the Negative Corona and Electrical Precipitation.—By W. W. Strong. (*Illustrated*) 1755

Law of Corona and Dielectric Strength of Air—III.—By F. W. Peek, Jr. (*Illustrated*) 1767
An Oscillograph Study of Corona.—By Edward Bennett. (*Illustrated*) 1787

MEETING AT VANCOUVER, SEPTEMBER 9-11, 1913.

Effects of Ice Loading on Transmission Lines.—By V. H. Greisser. (*Illustrated*) 1829
Mountain Railway Electrification.—By A. H. Babcock. (*Illustrated*) 1845
The Gulf of Georgia Submarine Telephone Cable. By E. P. LaBelle and L. P. Crim. (*Illustrated*) 1877
A Modern Substation in the Coeur D'Alene Mining District.—By John B. Fisken. (*Illustrated*) 1891

MEETING AT NEW YORK, OCTOBER 10, 1913.

Tungsten Lamps of High Efficiency—I.—By Irving Langmuir 1913
Tungsten Lamps of High Efficiency—II.—By Irving Langmuir and J. A. Orange. (*Illustrated*) 1935

MEETING AT PHILADELPHIA, PA., OCTOBER 13, 1913.

Industrial Substation.—By H. P. Liversidge. (*Illustrated*) 1955
Relation of Plant Size to Power Cost.—By P. M. Lincoln. (*Illustrated*) 1981

MEETING AT CHICAGO, ILL., OCTOBER 29, 1913.

Instability of Electric Circuits.—By Charles P. Steinmetz. (*Illustrated*) 2005

MEETING AT NEW YORK, NOVEMBER 14, 1913.

Dynamo Electric Lighting for Motor Cars.—By Alfred E. Waller. 2023
Advantages of Clutch Type Generator and Separate Starting and Lighting Units for Motor Cars.—By Alexander Churchward. (*Illustrated*) 2037
Electrical Equipment of Gasoline Automobiles.—By Frank Conrad (*Illustrated*) 2043

MEETING AT ANN ARBOR, MICH., DECEMBER 5, 1913.

Factors Determining a Reasonable Charge for Public Utility Service.—By M. E. Cooley 2077

MEETING AT NEW YORK, DECEMBER 12, 1913.

The Dielectric Strength of Thin Insulating Materials.—By F. M. Farmer. (*Illustrated*) 2097

MEETING AT SCHENECTADY, DECEMBER 16, 1913.

Power from Mercury Vapor.—W. L. R. Emmet. (*Illustrated*) .. 2133

APPENDIX

The I. E. C. Meeting at Berlin 2151
Report of Board of Directors for Fiscal Year Ending April 30, 1913. 2167

Index of papers and Discussions v
Index of Authors vii
Synoptical and Topical Index ..... End of Part II

INDEX.

PAPERS AND DISCUSSIONS.

Air as an Insulator when in the Presence of Insulating Bodies of Higher Specific Inductive Capacity. (Illustrated.) (*C. L. Fortescue and S. W. Farnsworth*) 893
Alternating-Current Motors for the Economic Operation of Mine Fans. (Illustrated.) (*F. B. Crosby*) 1073
Application of a Theorem of Electrostatics to Insulation Problems. The. (Illustrated.) (*C. Fortescue*) 907
Brush Friction and Contact Losses. (Illustrated.) (*H. F. T. Erben and A. H. Freeman*) 559
Calibration of the Sphere Gap Voltmeter, The. (Illustrated.) (*L. W. Chubb and C. Fortescue.*) 739
Central Station Power for Coal Mines. (*C. W. Beers.*) 1035
Central Station Power for Mines. (*J. S. Jenks*) 1097
Characteristics of Substation Loads at the Anthracite Collieries of the Lackawanna R. R. Co. (Illustrated.) (*H. M. Warren and A. S. Biesecker.*) 1103
Commutation and Brush Loss. (Illustrated.) (*C. E. Wilson.*) 577
Comparison of Methods of Loading Large A-C and D-C Generators and Synchronous Converters for Factory Temperature Tests. (Illustrated.) (*F. D. Newbury*) 649
Comparison of Methods of Making Load Tests on A-C Generators and on Induction Motors. (*E. F. Collins and W. E. Holcombe*) 667
Correction of Transformer Temperatures for Variation in Room Temperature, Taking into Account Both Copper and Iron Losses. (*C. Fortescue.*) 227
Current Rating of Electric Cables. (*Ralph W. Atkinson and H. W. Fisher.*) 325
Determination of Load Loss Correction Factors for Rotating Electric Machines. (Illustrated.) (*E. M. Olin and S. L. Henderson.*) 479
Determination of Stray Losses from Input-Output Tests. (Illustrated.) (*L. T. Robinson*) 531
Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electric Apparatus. (Illustrated.) (*C. E. Skinner, L. W. Chubb and Phillips Thomas.*) 279
Effect of Room Temperatures on Temperature Rise of Motors and Generators. (Illustrated.) (*Maxwell W. Day and R. A. Beekman.*) 259
Experimental Determination of the Regulation of Alternators, The. (Illustrated.) (*A. B. Field.*) 783
Generator and Prime Mover Capacities. (Illustrated.) (*D. B. Rushmore and Eric A. Lof.*) 795
Heating of Cables Carrying Current, The. (Illustrated.) (*Saul Dushman.*) 333
High Speed Turbo-Alternators—Designs and Limitations. (Illustrated.) (*B. G. Lamme*) 1
Induction Motor Load Losses. (Illustrated.) (*Henry G. Reist and A. E. Averett*) 423
Measurement of Temperature in Rotating Electric Machines. (Illustrated.) (*L. W. Chubb, E. I. Chute and O. W. A. Oetting.*) 163
Methods of Determining Brush Losses Due to Contact and Friction. (Illustrated.) (*H. R. Edgecomb and W. A. Dick.*) 565
Method of Determining Temperature of Alternating Current Generators and Motors and Room Temperature. (Illustrated.) (*Henry G. Reist and T. S. Eden.*) 177

Methods of Determining Temperature of Transformers. (Illustrated.) (*W. M. McConahey and C. Fortescue.*) 213
Methods of Determining Temperature of Transformers and of Cooling Medium. (Illustrated.) (*S. E. Johannesen and G. W. Wade.*) 191
Method of Rating Electrical Apparatus. (Illustrated.) (*W. L. Merrill, W. H. Powell and Charles Robbins.*) 91
Mining Loads for Central Stations. (Illustrated.) (*Wilfred Sykes and Graham Bright.*) 1121
Myriawatt, The. (*H. G. Stott and Haylett O'Neill.*) 411
Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions. (Illustrated.) (*C. B. Blanchard and C. T. Anderson.*) 289
Laws of Heat Transmission in Electrical Machinery. (*Irving Langmuir.*) 301
Load Losses of Alternating Current Generators. (Illustrated.) (*W. J. Foster and Edgar Knowlton.*) 503
Load Tests on Transformers. (Illustrated.) (*J. J. K. Madden.*) 691
Losses in Transformers. (Illustrated.) (*W. W. Lewis.*) 439
Notes on Induction Motor Losses. (*R. W. Davis.*) 435
Notes on Internal Heating of Stator Coils. (Illustrated.) (*R. B. Williamson.*) 153
Notes on Methods of Making Load Tests on Large Induction Motors. (*A. M. Dudley.*) 683
Notes on Stray Losses in Synchronous Machines. (*F. K. Brainard.*) 519
Operation of Transmission Lines. (Illustrated.) (*Lee Hagood.*) 855
Potential Waves of Alternating-Current Generators. (Illustrated.) (*W. J. Foster.*) 749
Proposed Wave Shape Standard, A. (Illustrated.) (*Cassius M. Davis.*) 775
Purchased Power in Coal Mines. (*H. C. Eddy.*) 1029
Radioactivity. (Illustrated.) (*Edwin Plimpton Adams.*) 953
Rating of Oil Circuit Breakers with Reference to Rupturing Capacity. (*George A. Burnham.*) 731
Regulation of Definite Pole Alternators. (Illustrated.) (*Soren H. Mortensen.*) 789
Safeguarding the Use of Electricity in Mines. (*H. H. Clark.*) 1055
Sources of Error in the Efficiency Determination of Rotating Electric Machines. (Illustrated.) (*Elmer I. Chute and William Bradshaw.*) 551
Sources of Error in Transformer Tests. (*W. M. McConahey and C. Fortescue.*) 703
Sphere Spark Gap, The. (Illustrated.) (*S. W. Farnsworth and C. L. Fortescue.*) 733
Stray Loss in Direct-Current Commutating Machines. (Illustrated.) (*H. F. T. Erben and H. S. Page.*) 523
Stray Losses in Induction Motors. (*A. M. Dudley.*) 429
Stray Losses in Transformers. (*C. Fortescue and W. M. McConahey.*) 465
Temperature and Electrical Insulation. (Illustrated.) (*C. P. Steinmetz and B. G. Lamme.*) 79
Temperature Rise of Stationary Induction Apparatus as Influenced by the Effects of Temperature, Barometric Pressure and Humidity of the Cooling Medium. (Illustrated.) (*J. J. Frank and W. O. Dwyer.*) 235
Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines. (Illustrated.) (*J. A. Capp and L. T. Robinson.*) 185
Wave Form Distortions and Their Effects on Electrical Apparatus. (Illustrated.) (*P. M. Lincoln.*) 765

INDEX OF AUTHORS

Adams, Comfort A., Discussion 57, 139, 143, 359, 374, 417, 590, 591, 595, 596, 612, 642, 821, 840, 845, 846, 847
Adams, Edwin Plimpton, Paper 953
Allen, C. E., Discussion 144
Anderson, C. T., Paper 289
Atkinson, Ralph W., Paper, 325; Discussion 385
Averrett, A. E., Paper, 423; Discussion 587, 589, 711
Bache-Wiig, Jens, Discussion 73
Beach, H. L., Discussion 1094
Beekman, R. A., Paper 259
Beers, C. W., Paper, 1035; Discussion 1052, 1087
Behrend, B. A., Discussion 110, 131, 132, 142, 374, 376, 587, 588, 590, 591, 592, 593, 594, 609, 614, 633, 635, 640, 642, 643, 716
Berkeley, L. R., Discussion 618
Biesecker, A. S., Paper 1103
Blanchard, C. B., Paper 289
Bradshaw, William, Paper 551
Brady, W. B., Discussion 609, 610
Brainard, F. K., Paper 519
Bright, Graham, Paper, 1121; Discussion 1066, 1091, 1110, 1113, 1146
Burke, James, Discussion 104, 126, 370, 377, 385, 420, 588, 590, 604, 606, 635, 642
Burnham, George A., Paper 731
Capp, J. A., Paper 185
Chubb, L. W., Paper, 163, 279, 739; Discussion, 365, 374, 384, 421, 821, 829, 838
Chute, E. I., Paper, 163, 551; Discussion 366, 644, 645, 714
Clark, H. H., Paper, 1055; Discussion 1070
Clayton, J. Paul, Discussion 1111, 1112
Clough, F. H., Discussion 74
Collins, E. F., Paper, 667; Discussion 628
Cory, C. L., Discussion 884, 891
Crocker, F. B., Discussion 101
Crosby, F. B., Paper, 1073; Discussion 1095
Crozier, Herbert W., Discussion 882, 883, 888, 889
Czeija, K. E., Discussion 64
Davis, Cassius M., Paper, 775; Discussion 845
Davis, R. W., Paper 435
Dawson, William F., Discussion 150, 359, 375, 394, 614, 646
Day, Maxwell W., Paper, 259; Discussion 360
Dick, W. A., Paper 565
Dickinson, W. E., Discussion 1050, 1067
Doyle, E. D., Discussion 831
Dreyfus, E. D., Discussion 1047
Dudley, A. M., Paper 429, 683
Durgin, W. A., Discussion 362
Dushman, Saul, Paper, 333; Discussion 359, 393
Dwyer, W. O., Paper 235
Eddy, H. C., Paper, 1029; Discussion 1051, 1091, 1142
Eden, T. S., Paper 177
Edgecomb, H. R., Paper 565
Edmonston, E. D., Discussion 406
Emmet, William LeRoy, Discussion 50

Erben, H. F. T., Paper, 523, 559; Discussion 632
Farmer, F. M., Discussion 831
Farnsworth, S. W., Paper, 733; Discussion 821, 893
Fast, B. M., Discussion 1093
Fechheimer, C. J., Discussion . . 46, 129, 396, 589, 591, 639, 642, 722 852
Field, A. B., Paper, 783; Discussion 62
Fisher, H. W., Paper 325
Fortescue, C., Paper, 213, 227, 465, 703, 733, 739, 893, 907; Discussion, 393, 394, 395, 398, 603, 606, 607, 726, 825, 828, 947
Foster, W. J., Paper, 503, 749; Discussion 64, 623, 634, 721
Francis, J. P., Discussion 891
Frank, J. J., Paper, 235; Discussion 393
Franklin, M. W., Discussion 826
Freeman, A. H., Paper, 559; Discussion 610
Gray, Alexander, Discussion 66, 122, 140, 375, 610, 612, 614, 716, 721, 847
Haar, Selby, Discussion 384
Hagood, Lee, Paper, 855; Discussion 882, 883, 884
Hall, H. Y., Discussion 891
Harper, John L., Discussion 619, 643
Harris, Ford W., Discussion 809
Hart, H. U., Discussion 109
Hellmund, R. E., Discussion 589, 590, 593, 595, 621, 712
Henderson, S. L., Paper, 479; Discussion 719
Herz, A., Discussion 401
Hobart, H. M., Discussion 53, 142, 361, 392, 418, 588, 593, 595, 645, 646, 718, 720
Holcombe, W. E., Paper 667
Jenks, J. S., Paper 1097; Discussion 1064
Johannesen, S. E., Paper 191
Jollyman, J. P., Discussion 888, 891
Jorgensen, L. P., Discussion 887
Junkersfeld, Peter, Discussion 52
Kaiser, G. K., Discussion 608
Kennelly, A. E., Discussion 143, 369, 383, 420, 836, 937
Knowlton, Edgar, Paper, 503; Discussion 722
Lamme, B. G., Paper, 1, 79, Discussion, 74, 121, 125, 130, 140, 363, 369, 376, 420, 589, 592, 613, 630, 647, 712, 713, 835, 852
Langmuir, Irving, Paper 301
Lauffer, C. A., Discussion 1063, 1065, 1066
Leeds, M. E., Discussion 363
Leilick, Frank T., Discussion 847
Lewis, W. W., Paper 439
Lichtenberg, Chester, Discussion 810
Lincoln, P. M., Paper, 765; Discussion 51, 608, 714, 807, 809, 825, 841, 1114, 1137
Lloyd, M. G., Discussion 116, 594, 727, 807, 836, 843
Lof, Eric A., Paper 795
Lundell, Robert, Discussion 370
MacGahan, Paul, Discussion 397
Madden, J. J. K., Paper, 691; Discussion 719
Mailloux, C. O., Discussion 360, 361, 931
Martindale, E. H., Discussion 618
McConahey, W. M., Paper 213, 465, 703
McCormick, Bradley T., Discussion 69
McNiece, T. M., Discussion 616, 619
Merrill, W. L., Paper 91; Discussion 135
Mershon, Ralph D., Discussion 929, 1066
Meyer-Delius, H., Discussion 1092
Morse, George H., Discussion 1047, 1112, 1118
Mortensen, Soren H., Paper 789
Muralt, C. L. de, Discussion 141

Newbury, F. D., Paper, 649; Discussion 371, 615, 625, 714, 716, 718, 720, 808, 845
Oetting, O. W. A., Paper 163
Olin, E. M., Paper, 479; Discussion 638
O'Neill, Haylett, Paper 411
Oschmann, W. O., Discussion 1093
Page, H. S., Paper 523
Palmer, L. R., Discussion 1069
Partridge, W., Discussion 1049
Pauly, K. A., Discussion 1046
Peart, L. N., Discussion 890
Peek, F. W., Jr., Discussion (Illustrated) 812, 934
Pen Dell, C. W., Discussion 1112, 1113, 1115, 1117, 1118
Porskievies, A. J., Discussion 715
Powell, R. C., Discussion 891
Powell, W. H., Paper, 91; Discussion 136
Randolph, C. P., Discussion 404
Reed, Taylor, Discussion 843
Reist, Henry G., Paper, 177, 423, Discussion 38, 119
Robbins, Charles, Paper 91
Robinson, L. T., Paper, 185, 531; Discussion 365, 370, 593, 607, 639, 641, 645, 843
Roper, D. W., Discussion 402
Rossman, A. M., Discussion 144
Rushmore, David B., Paper 795
Ryan, H. J., Discussion 946
Sandford, J. A., Jr., Discussion 820
Saunders, J. E., Discussion 606
Schuchardt, R. F., Discussion 124, 133, 365, 374
Schuler, Leo, Discussion, 106, 359, 361, 368, 374, 384, 420, 588, 606, 609, 621, 713, 715, 716, 719
Scott, Charles F., Discussion 137, 140, 606, 843
Seyfert, S. S., Discussion 722, 845
Sibley, Robert, Discussion 883
Skinner, C. E., Paper, 279; Discussion 125, 820, 828
Smith, George, Discussion 851
Smith, James M., Discussion 111, 125
Smith, W. C., Discussion 608
Stadeker, G. I., Discussion 147
Steinmetz, C. P., Paper 79; Discussion, 117, 128, 131, 134, 136, 362, 368, 370, 375, 383, 417, 419, 421, 587, 591, 593, 605, 637, 719, 826, 829, 834, 842
Stevenson, E. W., Discussion 385
Stone, Edmund C., Discussion 149, 404
Storer, S. B., Discussion 1144
Stott, H. G., Paper, 411; Discussion 106, 415
Swann, Theodore, Discussion 1139
Sykes, Wilfred, Paper, 1121; Discussion 1069, 1088
Thomas, Percy H., Discussion 823, 828, 926
Thomas, Phillips, Paper 279
Thomas, W. A., Discussion 1110
Torchio, Philip, Discussion (Illustrated). 42, 114, 130, 163, 151, 937
Treat, R. B., Discussion 614
Tynes, T. E., Discussion 1049, 1117
Underwood, L. E., Discussion 615
Vigo, Sidney G., Discussion 1116, 1137
Wade, G. W., Paper 191
Wagner, E. A., Discussion 146, 604
Wallau, H. L., Discussion 400
Warren, H. M., Paper, 1103; Discussion 1112, 1119
Waters, W. L., Discussion 56, 108, 850
Weaver, C. I., Discussion 1116

Weed, J. M., Discussion 394, 596, 606, 607, 608, 725, 726, 939
Welsh, J. W., Discussion 147
Wheeler, S. S., Discussion 113
Whitehead, J. B., Discussion 830
Williamson, R. B., Paper ,153; Discussion, 40, 376, 592, 712, 717
Wilson, C. E., Paper 577
Wood, George R., Discussion 1052, 1066, 1070, 1090, 1112, 1114

INDEX

PAPERS AND DISCUSSIONS

Advantages of Clutch Type Generator and Separate Starting and Lighting Units for Motor Cars. (Illustrated.) *Alexander Churchward* 2037
Automatic Methods in Long Distance Telephone Operation. (Illustrated.) *H. M. Friendly and A. E. Burns* 1305
Automatic Substations. (Illustrated.) *H. R. Summerhayes* 1685
Behavior of Synchronous Motors during Starting. (Illustrated.) *F. D. Newbury* 1509
Commutating-Pole Saturation in D-C. Machines. (Illustrated.) *Harold E. Stokes* 1527
Constant Voltage Transmission. (Illustrated.) *H. B. Dwight* 1545
Converting Substations in Basements and Sub-Basements. (Illustrated.) *B. G. Jamieson* 1699
Dielectric Strength of Thin Insulating Materials. (Illustrated.) *F. M. Farmer* 2097
Dynamo Electric Lighting for Motor Cars. *Alfred E. Waller* 2023
Effects of Ice Loading on Transmission Lines. (Illustrated.) *V. H. Greisser* 1829
Electric Strength of Air-IV, The. (Illustrated.) *J. B. Whitehead and T. T. Fitch* 1737
Electrical Equipment of Gasoline Automobiles. (Illustrated.) *Frank Conrad* 2043
Electrical Requirements of Certain Machines in the Rubber Industry. (Illustrated.) *C. A. Kelsey* 1583
Electrolytic Corrosion of Iron in Soils. (Illustrated.) *Burton McCollum and K. H. Logan* 1345
Factors Determining a Reasonable Charge for Public Utility Service. *M. E. Cooley* 2077
Gulf of Georgia Submarine Telephone Cable. (Illustrated.) *E. P. LaBelle and L. P. Crim* 1877
I. E. C. Meeting at Berlin, The 2151
Industrial Substations. (Illustrated.) *H. P. Liversidge* 1955
Industrial Use of Synchronous Motors by Central Stations, The. (Illustrated.) *John C. Parker* 1559
Instability of Electric Circuits. (Illustrated.) *Charles P. Steinmetz* 2005
Insulator Testing Specification for Insulators having an Operating Voltage exceeding 25,000 Volts. *Percy H. Thomas* 1471
Law of Corona and Dielectric Strength of Air—III. (Illustrated.) *F. W. Peek, Jr.* 1767
Modern Substation in the Coeur D'Alene Mining District, A. (Illustrated.) *John B. Fisken* 1891
Mountain Railway Electrification. (Illustrated.) *Allen H. Babcock* 1845
National Association of Corporation Schools, The. *F. C. Henderschott* 1413
Operation of Frequency Changers. (Illustrated.) *N. E. Funk* 1713
Oscillograph Study of Corona, An. (Illustrated.) *Edward Bennett* 1787
Pennsylvania Railroad Company Apprentice Schools, The. *John Price Jackson and J. W. L. Hale* 1437
Positive and Negative Corona and Electrical Precipitation, The. (Illustrated.) *W. W. Strong* 1755

Power from Mercury Vapor. (Illustrated.) *W. L. R. Emmet* ... 2133
Relation of Plant Size to Power Cost. (Illustrated.) *P. M. Lincoln* ... 1981
Report of Board of Directors for Fiscal Year Ending April 30, 1913 . 2167
Some Aspects of Institute Affairs. *Ralph D. Mershon* ... 1261
Standardization of Method for Determining and Comparing Power Costs in Steam Plants. (Illustrated.) *H. G. Stott and W. S. Gorsuch* ... 1619
Suggested Specifications for Testing High Voltage Insulators. *J. A. Sandford, Jr* ... 1462
Suggested Specifications for Testing High-Voltage Suspension Insulators. *F. W. Peek, Jr* ... 1457
Suggestion for the Engineering Profession, A. *William McClellan* . 1271
Test of an Artificial Aerial Telephone Line at a Frequency of 750 Cycles per Second. (Illustrated.) *A. E. Kennelly and F. W. Lieberknecht* ... 1283
Theory of the Non-Elastic and Elastic Catenary as Applied to Transmission Lines. *C. A. Pierce, F. J. Adams and G. L. Gilchrest* ... 1565
Trunk Line Electrification. (Illustrated.) *Charles P. Kahler* ... 1189
Tungsten Lamps of High Efficiency—I. Irving Langmuir ... 1913
Tungsten Lamps of High Efficiency—II. (Illustrated.) *Irving Langmuir and J. A. Orange* ... 1935
2400-Volt Railway Electrification. *H. M. Hobart* ... 1149
Vocational Education in Philadelphia and Vicinity. *A. J. Rowland* 1417

INDEX OF AUTHORS

Adams, Comfort A., Discussion 1450
Adams, F. J., Paper 1565
Armstrong, A. H., Discussion 1227
Babcock, Allen H., Paper, 1845; Discussion 1236, 1259
Bailey, Benjamin F., Discussion 2064
Barker, Harry, Discussion 1406, 1452
Bennett, Edward, Paper 1787; Discussion 1821
Blum, G. J., Discussion 2003
Bozell, Harold V., Discussion 1406
Brooks, G. W., Discussion 1976
Brown, R. S., Discussion 1338
Buck, A. M., Discussion 1448
Burns, A. E., Paper 1305
Caldwell, F. C., Discussion 1406, 1448, 1598, 1732
Campbell, George A., Discussion 1335
Carlton, W. G., Discussion 1668
Carron, Mr., Discussion 1449
Carter, F. W., Discussion 1242
Churchward, Alexander, Paper, 2037; Discussion 2069
Clarke, Chas., L., Discussion 1277, 1444
Colpitts, E. H., Discussion 1333, 1334
Conrad, Frank, Paper, 2043; Discussion 2071
Cooley, M. E., Paper 2077
Copley, Almon W., Discussion 2056
Crawford, M. T., Discussion 1446, 1491, 1598
Crecelius, L. P., Discussion 1666
Creighton, E. E. F., Discussion 1495
Crim, L. P., Paper 1877
Crozier, H. W., Discussion 1490, 1505
Dellenbaugh, Frederick S., Jr., Discussion 2072
Dell Plain, M. O., Discussion 1603
Dewey, H. H., Discussion 1610
Dreyfus, E. D., Discussion 1675
Dwight, H. B., Paper, 1545; Discussion 1599, 1601
Eglin, W. C. L., Discussion 1975, 1976, 1996
Emmet, W. L. R., Discussion 2133
Fales, H. M., Discussion 1952
Farmer, F. M., Paper, 2097; Discussion 2127
Fechheimer, C. J., Discussion 1615
Ferguson, O. J., Discussion 1450
Fisher, H. W., Discussion 2119
Fisken, John B., Paper, 1891; Discussion 1907, 1912
Fitch, T. T., Paper 1737
Flowers, Alan E., Discussion 1812, 1814, 1823, 1824
Floy, Henry, Discussion 1652
Forbes, Kingston, Discussion 2068
Foster, William J., Discussion 1589, 1612, 1613, 1614
Fraser, W., Discussion 1903
Friendly, H. M., Paper, 1305; Discussion 1344, 1449
Funk, N. E., Paper, 1713; Discussion 1597, 1604, 1736
Ganz, Albert F., Discussion 1407
Gilchrest, G. I., Paper 1565
Goodwin, Harold, Jr., Discussion 1978, 2060

Gorsuch, W. S., Paper, 1619; Discussion 1672
Greisser, V. H., Paper 1829
Hagood, Lee, Discussion 1596, 1601
Hale, J. W. L., Paper, 1437; Discussion 1446
Hall, H. Y., Discussion 1238
Hammer, W. J., Discussion 1824
Hayden, J. L. R., Discussion 1404
Hayward, R. F., Discussion 1906
Henderschott, F. C., Paper 1413
Hewlett, E. M., Discussion 1502, 1504
Hill, George, Discussion 1234
Hipple, J. M., Discussion 1591, 1592
Hobart, H. M., Paper, 1149; Discussion 1256, 1589, 1592, 1595, 1611, 1613, 1614, 1671, 1732, 2125
Horner, H. A., Discussion 1993
Howell, John W., Discussion 1947
Hunt, W. V., Discussion 1903
Jackson, D. C., Discussion 1280, 1333, 1405, 1669
Jackson, John Price, Paper, 1437; Discussion 2002
Jackson, R. P., Discussion 2116
Jamieson, B. G., Paper 1699
Junkersfeld, Peter, Discussion 1662
Kahler, Charles P., Paper, 1189; Discussion 1247
Karapetoff, V., Discussion 1907
Kebler, Leonard, Discussion 2053
Kelsey, C. A., Paper 1583
Kennelly, A. E., Paper, 1283; Discussion 2125
King, John R., Discussion 2074
Koganei, H., Discussion 1491
Kruesi, August H., Discussion 1589, 1668
Labelle, E. P., Paper 1877
Langmuir, Irving, Paper, 1913, 1935; Discussion 1951, 1952
Leonard, H. Ward, Discussion 2052
Libby, A. D. T., Discussion 2059
Lieb, John W., Jr., Discussion 1951
Leiberknecht, F. W., Paper 1283
Lighthipe, J. A., Discussion 1904, 1912
Lincoln, J. C., Discussion 1407, 1601, 1602, 1610, 1735
Lincoln, P. M. Paper, 1981; Discussion 1494, 1672, 1732, 1814, 1815, 1819, 1976 2003
Liversidge, H. P., Paper, 1955; Discussion 1979
Lloyd, M. G., Discussion 1951, 2000
Logan, K. H., Paper 1345
Mailloux, C. O., Discussion 1275, 1279, 1493, 1662, 1997 2001
Mathews, John, Discussion 1976
Maxwell, Alexander, Discussion 1404
McClellan, William, Paper, 1271; Discussion 1660, 1951
McCollum, Burton, Paper, 1345; Discussion 1409 1599
McMurtry, Alden L., Discussion 2071
Merriell, F. C., Discussion 1244
Merrill, W. L., Discussion 1608, 1613
Mershon, Ralph D., Paper, 1261; Discussion 1498, 1502, 1670, 1672
Middleton, W. I., Discussion 2126
Miller, A. A., Discussion 1905
Milnor, J. W., Discussion 2128
Muralt, C. L. de, Discussion 1278, 1280
Murray, W. S., Discussion 1235
Newbury, F. D., Paper, 1509; Discussion 1589, 1590, 1592, 1598, 1601, 1602, 1609, 1610, 1611, 1612, 1731
Nicholson, L. C., Discussion 1488, 1492
Nims, Frederick D., Discussion 1903
Orange, J. A., Paper 1935
Osgood, Farley, Discussion 1950, 1952

Parker, John C., Paper 1559
Parshall, H. F., Discussion 1245
Peck, Henry W., Discussion 1598, 1603, 1733
Peek, F. W., Jr., Paper, 1457, 1767; Discussion 1480, 1491, 1812, 1819, 2111
Penrose, Charles, Discussion 1977
Pierce, C. A., Paper 1565
Pope, R. W., Discussion 1906
Pratt, W. H., Discussion 1814
Randall, J. E., Discussion 1950
Robinson, L. T., Discussion 1810, 1817
Robinson, L. G., Discussion 1904
Roper, D. W., Discussion 1736
Rosa, E. B., Discussion 2122
Rowland, A. J., Paper, 1417; Discussion 1453
Ruffner, Charles S., Discussion 1676
Rushmore, D. B., Discussion 1277, 1665, 1731
Ryan, Harris, J., Discussion 1825
Sandford, J. A., Jr., Paper, 1462; Discussion 1482, 1491, 1492
Schwartz, Carl, Discussion 1655
Scott, C. F., Discussion 1508, 1810
Shaad, George C., Discussion 1450
Sharp, Clayton H., Discussion 2123
Skinner, C. E., Discussion 2117
Smith, Oberlin, Discussion 1280, 1344
Smith, Roger T., Discussion 1252
Sothman, P. W., Discussion 1506, 1671
Sprong, S. D., Discussion 1682, 1733
Steinmetz, Charles P., Paper, 2005; Discussion 1605, 1609, 1611, 1614
Stephens, P. V., Discussion 1977, 1997
Stokes, Harold E., Paper, 1527; Discussion 1592
Stott, H. G., Paper 1619; Discussion 1407, 1445
Strong, W. W., Paper 1755
Summerhayes, H. R., Paper, 1685; Discussion 1734, 1735
Taylor, J. B., Discussion 1343, 1813, 1814, 1947, 2124
Terrell, C. F., Discussion 1904
Thomas, Percy H., Paper, 1471; Discussion 1486, 1489, 1490, 1492, 1494, 1501, 1502, 1504
Thomas, Phillips, Discussion 2115
Tressler, M. E., Discussion 2120
Vreeland, F. K., Discussion 1333, 1334
Waller, Alfred E., Paper, 2023; Discussion 2070
Wayne, J. Lloyd, Discussion 1447
Welsh, G. W., Discussion 1238
Whitehead, J. B., Paper, 1737; Discussion 1811, 1815, 1817, 1821, 1823, 1824, 1825
Williamson, R. B., Discussion 1593, 1608, 1613
Wilson C. E., Discussion 2061
Wilson, J. H., Discussion 1611
Wreaks, Hugh T., Discussion 1406, 1495
Wynne, F. E., Discussion 1230

SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXXII, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

		Page
1.	Education	3
2.	General Theory	3
3.	Units, Measurements and Instruments	9
4.	Insulation and Dielectric Phenomena	19
5.	Electric Conductors	23
6.	Magnetic Properties and Testing of Iron	
7.	Batteries	
8.	Transformers	24
9.	Electrical Machinery and Apparatus	30
10.	Prime Movers and Steam Boilers	39
11.	Central Stations	40
12.	Parallel Operation	42
13.	Transmission Lines	42
14.	Electric Service Disturbances and Protection	
15.	Distribution Systems	44
16.	Control, Regulation and Switching	46
17.	Traction	48
18.	Lighting and Lamps	49
19.	Electricity in the Army and Navy	
20.	Miscellaneous Applications of Electricity	50
21.	Telephony and Telegraphy	53
22.	Miscellaneous Topics and Institute Affairs	53

1. EDUCATION

THE NATIONAL ASSOCIATION OF CORPORATION SCHOOLS

F. C. Henderschott — **Vol. xxxii—1913, pp. 1412-1416**

Purpose of organization of the National Association.

Discussion incorporated with that of paper by John Price Jackson and J. W. L Hale on "The Pennsylvania Railroad Company Apprentice Schools."

VOCATIONAL EDUCATION IN PHILADELPHIA AND VICINITY

A. J. Rowland — **Vol. xxxii—1913, pp. 1417-1435**

Electrical engineering phase of vocational education—the problem and possible solutions. Descriptions of conditions and needs in Philadelphia and how they are met. Brief description of courses given in a large number of schoo's in and around Philadelphia.

Discussion incorporated with that of paper by John Price Jackson and J. W. L. Hale on "The Pennsylvania Railroad Company Apprentice Schools."

THE PENNSYLVANIA RAILROAD COMPANY APPRENTICE SCHOOLS

John Price Jackson and J. W. L. Hale — **Vol. xxxii—1913, pp. 1437-1443**

Brief description of the organization, methods and work of the Pennsylvania Railroad School system

Discussion (including that of papers by F. C. Henderschott and A. J. Rowland) pages 1444-1455, by Messrs. Charles L. Clarke, Henry G. Stott, M. T. Crawford, J. W. L. Hale, J. Lloyd Wayne, 3rd, A. M. Buck, F. C. Caldwell, H. M. Friendly, Mr. Carron, George C. Shaad, O. J. Ferguson, Comfort A. Adams, Harry Barker and Arthur J. Rowland.

General remarks on vocational education. Experience of various teachers. Competitive education and the sorting of raw material.

2. GENERAL THEORY

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme — **Vol. xxxii—1913, pp. 78-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials with respect to working temperature. General character of heat flow in electrical machinery Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on "Methods of Rating Electrical Apparatus."

NOTES ON INTERNAL HEATING OF STATOR COILS

R. B. Williamson — **Vol. xxxii—1913, pp. 153-162**

Development of method of determining by calculation the maximum temperature in the stator coils for a given apparatus. Heat conductance of various commercial substances.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer **Vol. xxxii—1913, pp. 235-258**

Brief review of the quantitative relation between temperature and heat dissipation by radiation, convection and conduction and effect of room temperature, barometric pressure and moisture in each case. Experimental investigation of the effects of the last named factors in temperature tests of transformers. Recommendations for correction factors of transformer, classified by methods of cooling. Results of tests plotted as curves.

Discussion under Group I.

EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

Maxwell W. Day and R. A. Beekman **Vol. xxxii—1913, pp. 259-278**

Account of special tests on various types of motors and generators in a closed room prov ded with facilities for varying and controlling the temperature of the surrounding air. Development of method of determining room temperature correction factor from observed temperature at other than standard room temperature. Temperatures in various parts of machines plotted for different methods of ventilation and room temperatures. Room temperature correction factors for various types of machines tabulated.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

Discussion under Group I.

A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson **Vol. xxxii—1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

Discussion under Group I.

LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir **Vol. xxxii—1913, pp. 301-323**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials; also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of material. Extensive references to literature of the world on the subject of heat dissipation. Application of film theory of convection under various conditions. Results compared with older formulas.

Discussion under Group I.

DISCUSSION GROUP I PAPERS

pp. 152-387

Heating, Heat Measurements, Rating By Heat

(a) *Moving Machinery*

Notes on Internal Heating of Stator Coils, By R. B. Williamson.

Measurement o' Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(b) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(c) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(d) *Cable Heating*

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

Discussion pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmond C. Stone, C. P. Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity and different types of cables. Temperature rise calculations.

POTENTIAL WAVES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster **Vol. xxxii—1913, pp. 749-764**

Collection of e.m.f. wave shapes to show: first, the evolution of a. c. generators; second, the effect of load and no-load shapes; third, typical waves of machinery in extensive commercial service.

Discussion under Group IV.

WAVE DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

P. M. Lincoln **Vol. xxxii—1913, pp. 765-774**

General remarks on wave distortion and criticism of Institute 10 per cent Rule. Discussion illustrated by analysis of few actual cases.

Discussion under Group IV.

A PROPOSED WAVE SHAPE STANDARD

Cassius M. Davis **Vol. xxxii—1913, pp. 775-782**

Criticism of Institute 10 per cent Rule and definite suggestions for new rules. Also description of apparatus and method of measuring the proposed distortion ratio Appendix giving derivation of distortion ratio.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 781-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

THE APPLICATION OF A THEOREM OF ELECTRO-STATICS TO INSULATION PROBLEMS

C. Fortescue **Vol. xxxii—1913, pp. 907-926**

Mathematical analysis of electric field about a sphere and various other geometric shapes. Application of flux distribution theory to design of core and shell-type transformer insulation. Diagrammatic illustrations of transformer insulation construction. Pin and suspension type line insulators designed upon same principles. 1,000,000-volt transformer.

Discussion (including that of paper by Messrs. C. L. Fortescue and S. W. Farnsworth), pages 926-951, by Messrs. Percy H. Thomas, Ralph D. Mershon, C. O. Mailloux, F. W. Peek, Jr., A. E. Kennelly, Philip Torchio, J. Murray Weed, Harris J. Ryan and C Fortescue.

General remarks on insulation design and the dielectric circuit. Sharp criticism and hearty praise of author's papers. Effect of lightning stroke and high frequency upon insulator design. Limitations of condenser type terminals. Effect of frequency, external bodies, surface conduction upon insulation design.

RADIOACTIVITY

Edwin Plimpton Adams **Vol. xxxii—1913, pp. 953-1027**

Series of lectures upon radioactivity and the electronic theory tak ng up the fundamental principles of physics, chemistry and electricity and explaining them in the light of the electronic theory. Examples of the simpler calculations and description of experimental methods.

No discussion.

ELECTROLYTIC CORROSION OF IRON IN SOILS

Burton McCollum and K. H. Logan **Vol. xxxii—1913, pp. 1345-1403**

Experimental investigation of electro'ysis of iron in soil from various cities taking up each variable factor separately and determining its influence upon corrosion. Effect of current density, moisture, temperature, depth of burial, oxygen, kind of iron, chemicals in soil, etc. upon corrosion efficiency. Experimental study of earth resistance and the factors that affect it. Detailed description of tests and tabulation of results.

Discussion, pages 1404-1412, by Messrs. J. L. R. Hayden, Alexander Maxwell, D. C. Jackson, Hugh T. Wreaks, Harold V. Bozell, Harry Barker, F. C. Caldwell, J. C. Lincoln, Henry G. Stott, Albert F. Ganz and Burton McCollum.

General remarks on electrolysis from street railway currents and its prevention.

THEORY OF THE NON-ELASTIC AND ELASTIC CATENARY AS APPLIED TO TRANSMISSION LINES

C. A. Pierce, F. J. Adams and G. I. Gilchrest **Vol. xxxii—1913, pp. 1566-1581**

Mathematical development of catenary curve and deduction of simple equations for practical calculations. Experimental results compared with calculations by the author's method.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrica' Requirements of Certain Machines n the Rubber Industry."

THE ELECTRIC STRENGTH OF AIR.—IV

J. B. Whitehead and T. T. Fitch **Vol. xxxii—1913, pp. 1737-1753**

Description of tests and apparatus and discussion of results of a series of investigations on the effects of pressure, temperature and density upon

the formation of corona. Results tabulated and plotted as curves. Review of earlier work on corona. Application of ionization theory to corona formation. Bibliography of corona and dielectric strength of air.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION
W. W. Strong **Vol. xxxii—1913, pp. 1755-1765**

Investigation of corona losses with uni-directional current in apparatus designed for the utilization of corona for precipitating dust, smoke, etc. from fumes. Description of apparatus and tests. Results tabulated and plotted as curves for both directions of the current.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR.—III
F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1767-1785**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure above and below atmosphere, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper of Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA
Edward Bennett **Vol. xxxii—1913, pp. 1787-1809**

Experimental investigation of corona by means of oscillograms of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong, and F. W. Peek, Jr.,) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett William J. Hammer, and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

INSTABILITY OF ELECTRIC CIRCUITS
Charles P. Steinmetz **Vol. xxxii—1913, pp. 2005-2021**

Analysis of transient, unstable equilibrium and permanently unstable conditions in electric circuits using practical examples of each to explain the principles involved. Electrical equilibrium as affected by switching, formation of arcs, unstable loading of induction motors, hunting of synchronous machines, etc. Equations for use in determination of synchronizing and damping powers in synchronous machines.

No discussion.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer **Vol. xxxii—1913, pp. 2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering varnished cloth, hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, H. W. Fisher, M. E. Tressler, E. B. Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, H. M. Hobart, W. I. Middleton, F. M. Farmer, and J. W. Milnor.

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liquids and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

3. UNITS MEASUREMENTS AND INSTRUMENTS

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme **Vol. xxxii—1913, pp. 73-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials with respect to working temperature. General character of heat flow in electrical machinery. Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on "Methods of Rating Electrical Apparatus."

MEASUREMENT OF TEMPERATURE IN ROTATING ELECTRIC MACHINES

L. W. Chubb, E. I. Chute and O. W. A. Oetting **Vol. xxxii—1913, pp. 163-175**

Criticisms and comments on the thermometer and resistance methods of measuring temperature of electrical machinery. Description of special methods of temperature measurement including resistance exploring coils and thermocouples. Tests of temperature distribution in iron and copper of revolving field generator. Criticism of present standardization rules on temperature limits and measurements. List of recommendations for improved rules.

Discussion under Group I.

METHOD OF DETERMINING TEMPERATURE OF ALTERNATING CURRENT GENERATORS AND MOTORS AND ROOM TEMPERATURE

Henry G. Reist and T. S. Eden **Vol. xxxii—1913, pp. 177-184**

Experimental investigation of thermometer design for measurement of the true temperature of electrical machinery. Comparison of results with thermometer, resistance and exploring coil methods. Correction factors for temperature of enclosed machines.

Discussion under Group I.

THERMOCOUPLES AND RESISTANCE COILS FOR THE DETERMINATION OF LOCAL TEMPERATURES IN ELECTRICAL MACHINES

J. A. Capp and L. T. Robinson **Vol. xxxii—1913, pp. 185-190**

General analysis of the methods of measuring temperature in electrical machinery giving relative merits of thermometers change of resistance

of windings, resistance thermometers, special resistance coils and thermocouples.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS AND OF COOLING MEDIUM

S. E. Johannesen and G. W. Wade **Vol. xxxii—1913, pp. 191-211**

Analytical discussion of the various practical methods of measuring temperature with special reference to the effect of changes in the cooling conditions or room temperature. Tests showing the effect of using an idle transformer for determining the temperature lag correction factor. Recommendations for modifications of the standardization rules to cover use of idle transformer in temperature measurements.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS

W. M. McConahey and C. Fortescue **Vol. xxxii—1913, pp. 213-226**

Conditions affecting temperature of transformers under load. Testing effectiveness of cooling or ventilation. Methods of loading transformers for temperature tests, followed by description of alternate open and short-circuit method of testing a single transformer together with mathematical proof and actual test.

Discussion under Group I.

CORRECTION OF TRANSFORMER TEMPERATURES FOR VARIATION IN ROOM TEMPERATURE, TAKING INTO ACCOUNT BOTH COPPER AND IRON LOSSES

C. Fortescue **Vol. xxxii—1913, pp. 227-234**

Development of a method of calculating the temperature rise corresponding to standard room temperature when rise of any known room temperature has been observed.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer **Vol. xxxii—1913, pp. 235-258**

Brief review of the quantitative relation between temperature and heat dissipation by radiation, convection and conduction and effect of room temperature, barometric pressure and moisture in each case. Experimental investigation of the effects of the last named factors in temperature tests of transformers. Recommendations for correction factors of transformer, classified by methods of cooling. Results of tests plotted as curves.

Discussion under Group I.

EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

Maxwell W. Day and R. A. Beekman **Vol. xxxii—1913, pp. 259-278**

Account of special tests on various types of motors and generators in a closed room provided with facilities for varying and controlling the temperature of the surrounding air. Development of method of determining room temperature correction factor from observed temperature at other than standard room temperature. Temperatures in various parts of machines plotted for different methods of ventilation and room tempera-

tures. Room temperature correction factors for various types of machines tabulated.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

Discussion under Group I.

A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson **Vol. xxxii—1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

Discussion under Group I.

DISCUSSION GROUP 1 PAPERS

pp. 153-387

Heating, Heat Measurements, Rating by Heat

(*a*) *Moving Machinery*

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb, and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(d) Cable Heating

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher. The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer L. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity and different types of cables. Temperature rise calculations.

THE MYRIAWATT

H. G. Stott and Haylett O'Neill **Vol. xxxii—1913, pp. 411-414**

Introduction of term "myriawatt" followed by conversion factors of different units of energy and power and examples of the usefulness of the myriawatt in practical engineering calculations.

Discussion, pages 415-421, by Messrs. H. G. Stott, C. P. Steinmetz, Comfort A. Adams, Leo Schuler, H. M. Hobart, B. G. Lamme, James Burke, A. E. Kennelly, and L. W. Chubb.

Reasons for and against the adoption of myriawatt for boiler rating.

INDUCTION MOTOR LOAD LOSSES

Henry G. Reist and A. E. Averrett **Vol. xxxii—1913, pp. 422-428**

Discussion of the effect of load upon copper and core losses with different types of slot and winding construction, followed by tests and general conclusions as to effect of load losses.

Discussion under Group II.

STRAY LOSSES IN INDUCTION MOTORS

A. M. Dudley **Vol. xxxii—1913 pp. 429-434**

Discussion of load losses of induction motors of various sizes. Recommendations for standardization rules covering suggested method of determining load losses from no load tests.

Discussion under Group II.

NOTES ON INDUCTION MOTOR LOSSES

R. W. Davis **Vol. xxxii—1913, pp. 435-437**

Tabulated test results of stray losses in different sizes of induction motors.

Discussion under Group II.

LOSSES IN TRANSFORMERS

W. W. Lewis **Vol. xxxii—1913, pp. 439-462**

Experimental study of the no-load and load losses in different types of power transformers and high-tension instrument transformers showing the effect of changes in frequency, temperature, voltage and current. Re-

sults presented in tabular and graphic form. Recommendations for new rules defining transformer losses.

Discussion under Group II.

STRAY LOSSES IN TRANSFORMERS

C. Fortescue and W. M. McConahey **Vol. xxxii—1913, pp. 465-477**

Mathematical analysis of transformer resistance and inductance under load, no-load and short-circuit conditions. Suggested method of measuring short-circuit and impedance losses. Development of practical formulas for figuring regulation and stray losses. Recommendations for methods of obtaining losses and impedance voltage.

Discussion under Group II.

DETERMINATION OF LOAD LOSS CORRECTION FACTORS FOR ROTATING ELECTRIC MACHINES

E. M. Olin and S. L. Henderson **Vol. xxxii—1913, pp. 479-502**

Description and results of tests on d.c. and a.c. generators and synchronous converters to determine load losses and fix a correction factor that can be used with no-load measurements to get the true losses under load. Results in tabular and graphic form. Correction factors for well designed d.c. generators and motors, synchronous generators and motors, 25 and 60-cycle synchronous converters.

Discussion under Group II.

LOAD LOSSES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster and Edgar Knowlton **Vol. xxxii—1913, pp. 503-517**

Analytical discussion on load losses in a.c. generators and methods of determining them. Experimental investigation and comparison of various methods of measurement, including separation of losses, phase characteristic and circulating energy methods. Results in tabular and graphic form.

Discussion under Group II.

NOTES ON STRAY LOSSES IN SYNCHRONOUS MACHINES

F. K. Brainard **Vol. xxxii—1913, pp. 519-521**

Nature and determination of load losses in synchronous machines.

Discussion under Group II.

STRAY LOSS IN DIRECT-CURRENT COMMUTATING MACHINES

H. F. T. Erben and H. S. Page **Vol. xxxii—1913, pp. 523-529**

Description of method of testing machinery for load losses. Results of tests of number of a.c. machines given in form of loss-load curves.

Discussion under Group II.

THE DETERMINATION OF STRAY LOSSES FROM INPUT-OUTPUT TESTS

L. T. Robinson **Vol. xxxii—1913, pp. 531-550**

Analysis of factors that determine the precision of input-output efficiency tests. Tabulated results of a large number of tests to determine the degree of precision possible with commercial instruments and trained observers.

Discussion under Group II.

SOURCES OF ERROR IN THE EFFICIENCY DETERMINATION OF ROTATING ELECTRIC MACHINES

Elmer I. Chute and William Bradshaw **Vol. xxxii—1913, pp. 551-557**

Analytical discussion of errors due to instruments, observation and operating conditions Comparison of input-output and separation of losses, methods of determining efficiency.

Discussion under Group II.

BRUSH FRICTION AND CONTACT LOSSES

H. F. T. Erben and A. H. Freeman **Vol. xxxii—1913, pp. 559-564**

Experimental study of brush friction and contact resistance losses developing a practical method of calculation.

Discussion under Group II.

METHODS OF DETERMINING BRUSH LOSSES DUE TO CONTACT AND FRICTION

H. R. Edgecomb and W. A. Dick **Vol. xxxii—1913, pp. 565-576**

Analytical discussion of factors that enter into brush friction and contact resistance losses showing their relative importance. Supplemented by tests with special apparatus designed to furnish control of variable conditions.

Discussion under Group II.

COMMUTATION AND BRUSH LOSS

C. E. Wilson **Vol. xxxii—1913, pp. 577-584**

Experimental investigation and analysis of losses due to drop in brushes.

Discussion under Group II.

DISCUSSION GROUP II PAPERS

pp. 423-585

Methods of Determining Losses in Apparatus

(*a*) *Induction Motors*

Induction Motor Load Losses, by H. G. Reist and A. E. Averrett.

Stray Losses in Induction Motors, by A. M. Dudley.

Notes on Induction Motor Losses, by R. W. Davis.

(*b*) *Transformers*

Losses in Transformers, by W. W. Lewis.

Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(*c*) *Generators, A-C and D-C.*

Determination of load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.

Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.

Notes on Stray Losses in Synchronous Machines, by F. K. Brainard.

Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page

(*d*) *Errors of Tests*

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson.

Sources of Error in the Efficiency Determination of Rotating Electric Machines, by Elmer I. Chute and William Bradshaw.

(*e*) *Brush Losses*

Brush Friction and Contact Losses, by H. F. T. Erben and A. H. Freeman.

Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.

Commutation and Brush Losses, by C. E. Wilson.

Discussion, pages 587-648, by Messrs. A. E. Averrett, B. A. Behrend, C. P. Steinmetz, James Burke, H. M. Hobart, Leo Schuler, B. G. Lamme, R. E. Hellmund, C. J Fechheimer, Comfort A. Adams, R. B. Williamson, L. T. Robinson, M. G. Lloyd, J. M. Weed, C. Fortescue, E. A. Wagner, Charles F. Scott, J. E. Saunders, Paul M. Lincoln, W. C. Smith, G. K. Kaiser, W. B. Brady, A. H. Freeman, Alexander Gray, R. B. Treat, W. F. Dawson, P. D. Newbury, L. E. Underwood, T. M. McNiece, L. R. Berkeley and E. H. Martindale, John L. Harper, W. J. Foster, H. F. T. Erben, E. M. Olin and E. I. Chute.

Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

COMPARISON OF METHODS OF LOADING LARGE A-C. AND D-C. GENERATORS AND SYNCHRONOUS CONVERTERS FOR FACTORY TEMPERATURE TESTS

F. D. Newbury **Vol. xxxii—1913, pp. 649-665**

Classification and discussion of various methods of artificially loading rotating electrical machinery for operating temperature tests. Tests comparing various methods with actual energy load. Results tabulated.

Discussion under Group III.

COMPARISON OF METHODS OF MAKING LOAD TESTS ON A-C. GENERATORS AND ON INDUCTION MOTORS

E. F. Collins and W. E. Holcombe **Vol. xxxii—1913, pp. 667-681**

Brief description of most practical methods of obtaining mormal load temperature in a.c. generators and induction motors under no-load and partial load conditions. Comparisons of results with actual full load tests. Results in tabular form.

Discussion under Group III.

NOTES ON METHODS OF MAKING LOAD TESTS ON LARGE INDUCTION MOTOR

A. M. Dudley **Vol. xxxii—1913, pp. 683-690**

Brief description and discussion of loading back and artificial loading tests for induction motors. Comparison of series of tests by circulating current method with actual load test. Results tabulated

Discussion under Group III.

LOAD TEST ON TRANSFORMERS

J. J. K. Madden **Vol. xxxii—1913, pp. 691-701**

Brief description of various loading back tests on two or more transformers of different types. Description of method of testing single transformer for running temperature with artificial loading Results of tests tabulated and method of test recommended to Standards Committee.

Discussion under Group III.

SOURCES OF ERROR IN TRANSFORMER TESTS

W. M. McConahey and C. Fortescue **Vol. xxxii—1913, pp. 703-708**

Brief outline of various commercial tests of power transformers, pointing out possible errors and how to avoid them.

Discussion under Group III.

DISCUSSION GROUP III PAPERS

pp. 649-708

Method of Testing Apparatus for Performance

(*a*) *Generators and Induction Motors*

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests on A-C. Generators and on Induction Motors, by E. F. Collins and W. E. Holcombe.

Notes on Method of Making Load Test on Large Induction Motors, by A. M. Dudley.

(*b*) *Transformers*

Load Tests on Transformers, by J. J. K. Madden.

Sources of Error in Transformer Tests, by W. M. McConahey and C. Fortescue.

Discussion, pages 711-729, by Messrs. A. E. Averrett, R. B. Williamson, R. E. Hellmund, B. G. Lamme, Leo Schuler, E. I. Chute, Paul M. Lincoln, F. D. Newbury, A. J. Porskievies, Alexander Gray, B. A. Behrend, H. M. Hobart, Stuart L. Henderson, J. J. K. Madden, Charles P. Steinmetz, W. J. Foster, Edgar Knowlton, C. J. Fechheimer, J. M. Weed and M. G. Lloyd.

General remarks and opinions on methods of loading generators, motors and transformers artificially, based large y on experience. Suggested definition for transformer ratio.

THE SPHERE SPARK GAP

S. W. Farnsworth and C. L. Fortescue **Vol. xxxii—1913, pp. 733-737**

Criticisms of needle gap and recommendation of sphere gap to Standards Committee.

Discussion under Group IV.

THE CALIBRATION OF THE SPHERE GAP VOLTMETER

L. W. Chubb and C. Fortescue **Vol. xxxii—1913, pp. 739-748**

Description of results and method of calibration tests upon sphere gaps. Results plotted and tabulated for three different sizes of spheres.

Discussion under Group IV.

WAVE DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

P. M. Lincoln **Vol. xxxii—1913, pp. 765-774**

General remarks on wave distortion and criticism of Institute 10 per cent Rule. Discussion illustrated by analysis of few actual cases.

Discussion under Group IV.

A PROPOSED WAVE SHAPE STANDARD

Cassius M. Davis **Vol. xxxii—1913, pp. 775-782**

Criticism of Institute 10 per cent Rule and definite suggestions for new rules. Also description of apparatus and method of measuring the proposed distortion ratio. Appendix giving derivation of distortion ratio.

Discussion under Group IV.

THE EXPERIMENTAL DETERMINATION OF THE REGULATION OF ALTERNATORS

A. B. Field **Vol. xxxii—1913, pp. 783-787**

Criticisms of present Standardization Rules for specification and determination of regulation, followed by definite recommendations.

Discussion under Group IV.

REGULATION OF DEFINITE POLE ALTERNATORS

Soren H. Mortensen **Vol. xxxii—1913, pp. 789-794**

Description of method of determining regulation by Potier's triangle. Comparison of this method with Institute Rules method and with actual tests on a large number of three-phase, two-phase and single-phase machines. Results tabulated and saturation curves plotted for each method.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-904

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Swi ches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, E. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sanford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY

C. L. Fortescue and S. W. Farnsworth **Vol. xxxii—1913, pp. 855-905**

Development and method of designing solid insulation between two bodies so that the natural air field will not be altered; that is, so that the

max mum dielectric strength of the air along the surface of the insulator can be utilized. Description of apparatus for measuring and plotting equal potential curves in the electric field.

Discussion incorporated with that of paper by C. Fortescue on "The Application of a Theorem of Electrostatics to Insulation Problems."

TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND

A. E. Kennelly and F. W. Lieberknecht **Vol. xxxii—1913, pp. 1283-1303**

Detailed description and a series of tests on a very long artificial telephone line. E.m.f. and current being measured both as to phase and amplitude. Results tabulated and plotted as vector diagrams. Bibliography of articles of measurement on artificial telephone lines and allied topics.

Discussion incorporated with that of paper of Messrs. H. M. Friendly and A. E. Burns on "Automatic Methods in Long Distance Telephone Operation."

AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION

H. M. Friendly and A. E. Burns **Vol. xxxii—1913, pp. 1305-1332**

Description of equipment and operation of long distance automatic system of the Northwestern Long Distance Telephone Company.

Discussion (including that of paper by Messrs. A. E. Kennelly and F. W. Lieberknecht), pages 1333-1344, by Messrs. F. K. Vreeland, E. H. Colpitts, D. C. Jackson, George A. Campbell, R. S. Brown, J. B. Taylor, H. M. Friendly and Oberlin Smith.

Telephone line calculations. Definitions of iterative impedance and propagation constants. Use of integraph in solving equations.

ELECTROLYTIC CORROSION OF IRON IN SOILS

Burton McCollum and K. H. Logan **Vol. xxxii—1913, pp. 1345-1403**

Experimental investigation of electrolysis of iron in soil from various cities taking up each variable factor separately and determining its influence upon corrosion. Effect of current density, moisture, temperature, depth of burial, oxygen, kind of iron, chemicals in soil, etc. upon corrosion efficiency. Experimental study of earth resistance and the factors that affect it. Detailed description of tests and tabulation of results.

Discussion, pages 1404-1412, by Messrs. J. L. R. Hayden, Alexander Maxwell, D. C. Jackson, Hugh T. Wreaks, Harold V. Bozell, Harry Barker, F. C. Caldwell, J. C. Lincoln, Henry G. Stott, Albert F. Ganz and Burton McCollum.

General remarks on electrolysis from street railway currents and its prevention.

OPERATION OF FREQUENCY CHANGERS

N. E. Funk **Vol. xxxii—1913, pp. 1713-1730**

General review of theory of parallel operation of synchronous frequency changers. Detailed description of method of synchronizing with rotating synchroscope and a special synchronizing indicator. Examples of use of indicator.

Discussion (including that of papers by H. R. Summerhayes and B. G. Jamieson) pages 1731-1736, by Messrs. D. B. Rushmore, F. D. Newbury, F. C. Caldwell, Paul M. Lincoln, H. M. Hobart, Henry W. Peck, S. D.

Sprong, H. R. Summerhayes, J. C. Lincoln, D. W. Roper and N. E. Funk.

General remarks on the advisability of running machinery unattended. Oil pressure for facilitating the starting of large machines.

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1767-1788**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure above and below atmospheric, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett **Vol. xxxii—1913, pp. 1787-1809**

Experimental investigation of corona by means of oscillograms of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong and F.W. Peek, Jr.,) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett, William J. Hammer and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer **Vol. xxxii—1913, pp. 2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering varnished cloth, hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, H. W. Fisher, M. E. Tressler, E. B. Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, H. M. Hobart, W. I. Middleton, F. M. Farmer, and J. W. Milnor.

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liquids and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

4. INSULATION AND DIELECTRIC PHENOMENA

TEMPERATURE AND ELECTRICAL INSULATION

C. P. Steinmetz and B. G. Lamme **Vol. xxxii—1913, pp. 78-89**

Statement of the problem of temperature limitations of insulating materials used in electrical machines. Classification of insulating materials

with respect to working temperature. General character of heat flow in electrical machinery. Temperature measurement and recommendations for standardization of temperature limitations and methods of measurement.

Discussion incorporated with that of paper by Messrs. W. L. Merrill, W. H. Powell and Charles Robbins, on "Methods of Rating Electrical Apparatus."

METHODS OF RATING ELECTRICAL APPARATUS

W. L. Merrill, W. H. Powell and Charles Robbins — **Vol. xxxii—1913, pp. 91-100**

Recommendations for the standardization of electrical apparatus ratings according to a plan that will more truly represent the capability of the apparatus than the present rules. Ratings for different classes of service. Temperature limitation of different classes of insulation and different kinds of service. Recommendations for name plate stamping.

Discussion (including that of paper by Messrs. C. P. Steinmetz and B. G. Lamme), pages 101-152, by Messrs. F. B. Crocker, James Burke, Henry G. Stott, W. L. Waters, H. U. Hart, B. A. Behrend, James M. Smith, Schuyler Skaats Wheeler, P. Torchio, M. G. Lloyd, Charles P. Steinmetz, Henry G. Reist, B. G. Lamme, Alexander Gray, R. F. Schuchardt, C. E. Skinner, C. J. Fechheimer, W. L. Merrill, W. H. Powell, Charles F. Scott, Comfort A. Adams, C. L. de Muralt, H. M. Hobart, A. E. Kennelly, A. M. Rossman, C. E. Allen, E. A. Wagner, G. I. Stadeker, J. W. Welsh, Edmund C. Stone and William F. Dawson.

Comments and criticisms of the recommendations for standard methods of rating and limiting temperatures of electrical apparatus. Experience in the operation of electrical machinery with regard to safe operating temperature. American standardization rules compared with European standards. International Electro-technical Commission rules compared with Inst tute rules. Defense and explanation of the proposed new standardization rules.

THE SPHERE SPARK GAP

S. W. Farnsworth and C. L. Fortescue — **Vol. xxxii—1913, pp. 733-737**

Criticisms of needle gap and recommendation of sphere gap to Standards Committee.

Discussion under Group IV.

THE CALIBRATION OF THE SPHERE GAP VOLTMETER

L. W. Chubb and C. Fortescue — **Vol. xxxii—1913, pp. 739-748**

Description of results and method of calibration tests upon sphere gaps. Results plotted and tabulated for three different sizes of spheres.

Discussion under Group IV

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY

C. L. Fortescue and S. W. Farnsworth — **Vol. xxxii—1913, pp. 893-906**

Development and method of designing solid insulation between two bodies so that the natural air field will not be altered; that is, so that the maximum dielectric strength of the air along the surface of the insulator can be utilized. Description of apparatus for measuring and plotting equal potential curves in the electric field

Discussion incorporated with that of paper by C. Fortescue on "The Application of a Theorem of Electrostatics to Insulation Problems".

THE APPLICATION OF A THEOREM OF ELECTRO-STATICS TO INSULATION PROBLEMS

C. Fortescue **Vol. xxxii—1913, pp. 907-925**

Mathematical analysis of electric field about a sphere and various other geometric shapes. Application of flux distribution theory to design of core and shell-type transformer insulation. Diagrammatic illustrations of transformer insulation construction. Pin and suspension type line insulators designed upon same principles. 1,000,000-volt transformer.

Discussion (including that of paper by Messrs. C. L. Fortescue and S. W. Farnsworth), pages 926-951, by Messrs. Percy H. Thomas, Ralph D. Mershon, C. O. Mailloux, F. W. Peek, Jr., A. E. Kennelly, Philip Torchio, J. Murray Weed, Harris J. Ryan and C. Fortescue.

General remarks on insulation design and the dielectric current. Sharp criticism and hearty praise of author's papers. Effect of lightning stroke and high frequency upon insulator design. Limitations of condenser type terminals. Effect of frequency, external bodies, surface conduction upon insulation design.

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE SUSPENSION INSULATORS

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1457-1461**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS

J. A. Sandford, Jr. **Vol. xxxii—1913, pp. 1462-1470**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

INSULATOR TESTING SPECIFICATION FOR INSULATORS HAVING AN OPERATING VOLTAGE EXCEEDING 25,000 VOLTS

Percy H. Thomas **Vol. xxxii—1913, pp. 1471-1479**

Discussion (including that of papers by Messrs. F. W. Peek, Jr., and J. A. Sanford, Jr.) pages 1480-1508, by Messrs. F. W. Peek, Jr., J. A. Sanford, Jr., P. H. Thomas, L. C. Nicholson, H. W. Crozier, H. Koganei, M. T. Crawford, C. O. Mailloux, Paul M. Lincoln, Hugh T. Wreaks, E. E. F. Creighton, Ralph D. Mershon, E. M. Hewlett, P. W. Sothman and C. F. Scott.

Criticisms and suggestions for specifications for the design and testing of insulators. Effect of simultaneous mechanical and electrical stresses, tests.

THE ELECTRIC STRENGTH OF AIR—IV

J. B. Whitehead and T. T. Fitch **Vol. xxxii—1913, pp. 1737-1753**

Description of tests and apparatus and discussion of results of a series of investigations on the effects of pressure, temperature and density upon the formation of corona. Results tabulated and plotted as curves. Review of earlier work on corona. Application of ionization theory to corona formation. Bibliography of corona and dielectric strength of air.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION

W. W. Strong **Vol. xxxii—1913, pp. 1755-1766**

Investigation of corona losses with uni-directional current in apparatus designed for the utilization of corona for precipitating dust, smoke, etc. from fumes. Description of apparatus and tests. Results tabulated and plotted as curves for both directions of the current.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1767-1786**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure, above and below atmosphere, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett **Vol. xxxii—1913, pp. 1787-1809**

Experimental investigation of corona by means of oscillograms of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong, and F. W. Peek, Jr.) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett, William J. Hammer, and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

THE GULF OF GEORGIA SUBMARINE TELEPHONE CABLE

E. P. LaBelle and L. P. Crim **Vol. xxxii—1913, pp. 1877-1889**

Specifications for submarine cable load by Krarup system. Account of laying, splicing, locating faults, etc. Krarup continuous system compared with the Pupin coil system of loading.

No discussion.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

F. M. Farmer **Vol. xxxii—1913, pp. 2097-2110**

Description of method and results of tests to determine the effect of electrode area upon the apparent dielectric strength of insulating materials in comparatively thin sheets. Tests covering varnished cloth, hard rubber, oil and air under various conditions.

Discussion, pages 2111-2131, by Messrs. F. W. Peek, Jr., Phillips Thomas, R. P. Jackson, C. E. Skinner, H. W. Fisher, M. E. Tressler, E. B. Rosa, Clayton H. Sharp, John B. Taylor, A. E. Kennelly, H. M. Hobart, W. I. Middleton, F. M. Farmer and J. W. Milnor.

Account of experience in the testing of insulating materials with results and description of methods and apparatus. Theory of insulation strength of gases, liqu ds and solids. Mathematical demonstration of author's results with varying size of electrode by means of law probability.

5. ELECTRIC CONDUCTORS

CURRENT RATING OF ELECTRIC CABLES

Ralph W. Atkinson and H. W. Fisher **Vol. xxxii—1913, pp. 335-321**

Brief analytical discussion of heating of cables showing the relative importance of various factors that influence either the heating or the cooling. Formulas and tables for calculating the load capacity of various types and sizes of cables. Example of calculation.

Discussion under Group I.

THE HEATING OF CABLES CARRYING CURRENT

Saul Dushman **Vol. xxxii—1913, pp. 333-357**

Detailed description of current-carrying capacity and heating test upon certain cables together with results in tabular and graphic form. Discussion of the results developing from general application. Thermal properties of various cable insulating materials.

Discussion under Group I.

DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat Measurements, Rating by Heat

(*a*) *Moving Machinery*

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperatures of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank, and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure, and Humidity on The Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.
Laws of Heat Transmission in Electrical Machinery by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.
The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity and different types of cables. Temperature rise calculations.

8. TRANSFORMERS

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS AND OF COOLING MEDIUM

S. E. Johannesen and G. W. Wade — **Vol. xxxii—1913, pp. 191-211**

Analytical discussion of the various practical methods of measuring temperature with special reference to the effect of changes in the cooling conditions of room temperature. Tests showing the effect of using an idle transformer for determining the temperature lag correction factor. Recommendations for modification of the standardization rules to cover use of idle transformer in temperature measurements.

Discussion under Group I.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS

W. M. McConahey and C. Fortescue — **Vol. xxxii—1913, pp. 213-336**

Conditions affecting temperature of transformers under load. Testing effectiveness of cooling or ventilation. Methods of loading transformers for temperature tests, followed by description of alternate open and short-circuit method of testing a single transformer together with mathematical proof and actual tests.

Discussion under Group I.

CORRECTION OF TRANSFORMER TEMPERATURES FOR VARIATION IN ROOM TEMPERATURE, TAKING INTO ACCOUNT BOTH COPPER AND IRON LOSSES

C. Fortescue — **Vol. xxxii—1913, pp. 227-234**

Development of a method of calculating the temperature rise corresponding to standard room temperature when rise of any known room temperature has been observed.

Discussion under Group I.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

J. J. Frank and W. O. Dwyer — **Vol. xxxii—1913, pp. 235-258**

Brief review of the quantitative relation between temperature and heat dissipation by radiation, convection and conduction and effect of room temperature, barometric pressure and moisture in each case. Experimental investigation of the effects of the last named factors in temperature tests of transformers. Recommendations for correction factors of transformer, classified by methods of cooling. Results of tests plotted as curves.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas — **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

Discussion under Group I.

A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson — **Vol. xxxii—1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

Discussion under Group I.

LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir — **Vol. xxxii—1913, pp. 301-333**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials; also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of materials. Extensive references to literature of the world on the subject of heat dissipation. Application of film theory of convection under various conditions. Results compared with older formulas.

Discussion under Group I.

DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat, Measurements Rating by Heat

(*a*) *Moving Machinery*

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature on Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Funct on of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

Discussion pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mail oux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallay, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph, and E. D Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extens ve tests on current-carrying capacity of different types of cables Temperature rise calculations.

LOSSES IN TRANSFORMERS

W. W. Lewis **Vol. xxxii—1913, pp. 439-462**

Experimental study of the no-load and load losses in different types of power transformers and high-tension instrument transformers showing the effect of changes in frequency, temperature, voltage and current. Results presented in tabular and graphic form. Recommendations for new rules defining transformer losses.

Discussion under Group II

STRAY LOSSES IN TRANSFORMERS

C. Fortescue and W. M. McConahey **Vol. xxxii—1913, pp. 465-477**

Mathematical analysis of transformer resistance and inductance under load, no-load and short-circuit conditions. Suggested method of measuring short-circuit and impedance losses. Development of practical

formulas for figuring regulation and stray losses. Recommendations for methods of obtaining losses and impedance voltage.

Discussion under Group II.

DISCUSSION GROUP II PAPERS

pp. 433-585

Methods of Determining Losses in Apparatus

(*a*) *Induction Motors*

Induction Motor Load Losses, by H G. Reist, and A. E. Averrett.
Stray Losses in Induction Motors, by A. M. Dudley.
Notes on Induction Motor Losses, by R. W. Davis.

(*b*) *Transformers*

Losses in Transformers, by W. W. Lewis.
Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(*c*) *Generators, A-C and D-C.*

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.
Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.
Notes on Stray Losses in Synchronous Machines, by F. K Brainard.
Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page.

(*d*) *Error of Tests*

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson
Sources of Error in the Efficiency Determination of Rotating Electric Machines by Elmer I. Chute, and William Bradshaw.

(*e*) *Brush Losses*

Brush Friction and Contact Losses by H. F. T. Erben and A. H. Freeman.
Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.
Commutation and Brush Losses, by C. E. Wilson.

Discussion, pages 587-648, by Messrs. A. E. Averrett, B. A. Behrend, C. P. Steinmetz, James Burke, H. M. Hobart, Leo Schuler, B. G. Lamme, R. E. He lmund, C. J. Fechheimer, Comfort A. Adams, R. B. Williamson, L. T. Robinson, M. G. Lloyd, J. M. Weed, C. Fortescue, E. A. Wagner, Charles F. Scott, J. E. Saunders, Paul M. Lincoln, W. C. Smith, G. K. Kaiser, W. B. Brady, A. H. Freeman, Alexander Gray, R B. Treat, W. F. Dawson, F. D. Newbury, L. E. Underwood, T. M McNiece, L. R. Berkeley and E. H. Martindale, John L. Harper, W. J. Foster, H. F. T. Erben, E. M. Olin and E. I. Chute.

Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

LOAD TESTS ON TRANSFORMERS

J. J. K. Madden **Vol. xxxii—1913, pp. 691-702**

Brief description of various loading back tests on two or more transformers of different types. Description of method of testing single transformer for running temperature with artificial loading. Results of tests tabulated and method of test recommended to Standards Committee.

Discussion under Group III.

SOURCES OF ERROR IN TRANSFORMER TESTS

W. M. McConahey and C. Fortescue **Vol. xxxii—1913, pp. 703-708**

Brief outl ne of various commercial tests of power transformers, pointing out possible errors and how to avo d them.

Dis ussion under Group III.

DISCUSSION GROUP III PAPERS

pp. 649-708

Method of Testing Apparatus for Performance

(*a*) *Generators and Induction Motors*

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests on A-C. Generators and on Induction Motors, by E. F. Col ins and W. E. Holcombe.

Notes on Method of Making Load Tests on Large Induct on Motors, by A M. Dudley.

(*b*) *Transformers*

Load Test on Transformers, by J. J. K. Madden.

Source of Error in Transformer Tests by W M. McConahey and C. Fortescue

Discussion, pages 711-729, by Messrs. A E Averrett, R. B Williamson, R. E. Hellmund, B. G. Lamme, Leo Schuler, E.I. Chute, Pau M. Lincoln, F. D Newbury, A J. Porskievies, Alexander Gray B. A. Behrend, H. M. Hobart, Stuart L. Henderson J. J. K. Madden, Charles P. Steinmetz, W J Foster, Edgar Knowlton, C. J. Fechheimer J M Weed and M. G. Lloyd

General remarks and opinions on methods of loading generators, motors, and transformers artificially, based largely on experience. Suggested definition for transformer ratio.

WAVE DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

P. M. Lincoln **Vol. xxxii—1913, pp. 765-774**

General remarks on wave distortion and criticism of Inst tute 10 per cent Rule. Discussion illustrated by analysis of few actua cases.

Discuss on under Group IV.

A PROPOSED WAVE SHAPE STANDARD

Cassius M. Davis **Vol. xxxii—1913, pp. 775-783**

Criticism of Institute 10 per cent Rule and definite suggestions for new rules. Also description of apparatus and method of measuring the proposed distortion ratio. Appendix giving derivation of distortion ratio.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*d*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Löf.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

THE APPLICATION OF A THEOREM OF ELECTRO-STATICS TO INSULATION PROBLEMS

C. Fortescue — Vol. xxxii—1913, pp. 907-925

Mathematical analysis of electric field about a sphere and various other geometric shapes. Application of flux distribution theory to design of core and shell-type transformer insulation. Diagrammatic illustrations of transformer insulation construction. Pin and suspension type line insulators designed upon same principles. 1,000,000-volt transformer.

Discussion (including that of paper by Messrs. C. L. Fortescue and S. W. Farnsworth), pages 926-951, by Messrs. Percy H. Thomas, Ralph D. Mershon, C. O. Mailloux, F. W. Peek, Jr., A. E. Kennelly, Philip Torchio, J. Murray Weed, Harris J. Ryan and C. Fortescue.

General remarks on insulation design and the dielectric circuit. Sharp criticism and hearty praise of author's papers. Effect of lightning stroke and high frequency upon insulator design. Limitations of condenser type terminals. Effect of frequency, external bodies, surface conduction upon insulation design.

9. ELECTRICAL MACHINERY AND APPARATUS

HIGH SPEED TURBO-ALTERNATORS—DESIGNS AND LIMITATIONS

B. G. Lamme **Vol. xxxii—1913, pp. 1-37**

Analytical discussion of developments and present status of turbo-alternator design, covering general mechanical construction, vibration, temperature rise and distribution, insulation losses, regulation and all other important factors that enter into the problem. The paper is especially complete as to ventilation, temperature and insulation.

Discussion, pages 38-78, by Messrs. Henry G. Reist, R. B. Williamson, Philip Torchio, C. J. Fechheimer, William LeRoy Emmet, Paul M. Lincoln, Peter Junkersfeld, H. M. Hobart, W. L. Waters, Comfort A. Adams, Allan B. Field, W. J. Foster, K. E. Czeija, Alexander Gray, Bradley T. McCormick, Jens Bache-Wiig, F. H. Clough and B. G. Lamme.

General remarks on turbo-alternator design. Some difficulties encountered in operation. Equation for maximum output. Much data and experience on ventilation and insulation of turbo-alternators. Analysis of heat flow and temperature distribution.

METHODS OF RATING ELECTRICAL APPARATUS

W. L. Merrill, W. H. Powell and Charles Robbins **Vol. xxxii—1913, pp. 91-100**

Recommendations for the standardization of electrical apparatus ratings according to a plan that will more truly represent the capability of the apparatus than the present rules. Ratings for different classes of service. Temperature limitation of different classes of insulation and different kinds of service. Recommendations for name plate stamping.

Discussion (including that of paper by Messrs. C. P. Steinmetz and B. G. Lamme), pages 101-152, by Messrs. F. B. Crocker, James Burke, Henry G. Stott, W. L. Waters, H. U. Hart, B. A. Behrend, James M. Smith, Schuyler Skaats Wheeler, P. Torchio, M. G. Lloyd, Charles P. Steinmetz, Henry G. Reist, B. G. Lamme, Alexander Gray, R. F. Schuchardt, C. E. Skinner, C. J. Fechheimer, W. L. Merrill, W. H. Powell, Charles F. Scott, Comfort A. Adams, C. L. de Muralt, H. M. Hobart, A. E. Kennelly, A. M. Rossman, C. E. Allen, E. A. Wagner, G. I. Stadeker, J. W. Welsh, Edmund C. Stone and William F. Dawson.

Comments and criticisms of the recommendations for standard methods of rating and limiting temperatures of electrical apparatus. Experience in the operation of electrical machinery with regard to safe operating temperature. American standardization rules compared with European standards. International Electro-technical Commission rules compared with Institute rules. Defence and explanation of the proposed new standardization rules.

NOTES ON INTERNAL HEATING OF STATOR COILS

R. B. Williamson **Vol. xxxii—1913, pp. 153-163**

Development of method of determining by calculation the maximum temperature in the stator coils for a given apparatus. Heat conductance of various commercial substances.

Discussion under Group I.

MEASUREMENT OF TEMPERATURE IN ROTATING ELECTRIC MACHINES

L. W. Chubb, E. I. Chute and O. W. A. Oetting **Vol. xxxii—1913, pp. 143-176**

Criticisms and comments on the thermometer and resistance methods of measuring temperature of electrical machinery. Description of special methods of temperature measurement including resistance exploring coils and thermocouples. Tests of temperature distribution in iron and copper of revolving field generator. Criticism of present standardization rules on temperature limits and measurements. List of recommendations for improved rules.

Discussion under Group I.

METHOD OF DETERMINING TEMPERATURE OF ALTERNATING CURRENT GENERATORS AND MOTORS AND ROOM TEMPERATURE

Henry G. Reist and T. S. Eden **Vol. xxxii—1913, pp. 177-184**

Experimental investigation of thermometer design for measurement of the true temperature of electrical machinery. Comparison of results with thermometer, resistance and exploring coil methods. Correction factors for temperature of enclosed machines.

Discussion under Group I.

THERMOCOUPLES AND RESISTANCE COILS FOR THE DETERMINATION OF LOCAL TEMPERATURES IN ELECTRICAL MACHINES

J. A. Capp and L. T. Robinson **Vol xxxii—1913, pp. 185-190**

General analysis of the methods of measuring temperature in electrical machinery giving relative merits of thermometers, change of resistance of windings, resistance thermometers, special resistance coils and thermocouples.

Discussion under Group I.

EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

Maxwell W. Day and R. A. Beekman **Vol. xxxii—1913, pp. 289-278**

Account of special tests on various types of motors and generators in a closed room provided with facilities for varying and controlling the temperature of the surrounding air. Development of method of determining room temperature correction factor from observed temperature at other than standard room temperature. Temperatures in various parts of machines plotted for different methods of ventilation and room temperatures. Room temperatures correction factors for various types of machines tabulated.

Discussion under Group I.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

C. E. Skinner, L. W. Chubb and Phillips Thomas **Vol. xxxii—1913, pp. 279-288**

Account of test upon a coil in a closed space where surrounding conditions are under control. Results of tests and conclusions regarding application of correction factors to room temperature for reduction of results to standard conditions.

Discussion under Group I.

A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

C. B. Blanchard and C. T. Anderson **Vol. xxxii—1913, pp. 289-299**

Description of apparatus and tests giving results in tabular and graphic form. Effects of atmospheric temperature, pressure and moisture considered separately.

Discussion under Group I.

LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

Irving Langmuir **Vol. xxxii—1913, pp. 301-323**

Review of theory of heat conduction, radiation and convection. Tables of thermal conductivity and resistivity of various electrical materials, also emissivity of various metal surfaces. Temperature coefficient of heat resistivity, emissivity and convection with different kinds of materials. Extensive references to literature of the world on the subject of heat dissipation: Application of film theory of convection under various conditions. Results compared with older formulas.

Discussion under Group I.

DISCUSSION GROUP I PAPERS

pp. 153-357

Heating, Heat Measurements, Rating by Heat

(*a*) *Moving Machinery*

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature of Rotating Electric Machines, by L. W. Chubb, E. I. Chute, and O. W. A. Oetting.

Methods of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(*b*) *Transformers*

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Measuring Temperature of Transformers, by C. Fortescue and W. M. McConahey.

Correction of Transformer Temperature for Variation of Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(*c*) *Temperature Correction*

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(*d*) *Cable Heating*

Current Rating of Electric Cables by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

Discussion, pages 359-409, by Messrs. Comfort A. Adams, S. Dushman, William F. Dawson, Leo Schuler, C. O. Mailloux, M. W. Day, H. M. Hobart, Charles P. Steinmetz, W. A. Durgin, B. G. Lamme, M. E. Leeds, L. W. Chubb, L. T. Robinson, R. F. Schuchardt, Elmer I. Chute, A. E. Kennelly, James Burke, Robert Lundell, F. D. Newbury, B. A. Behrend, Alexander Gray, R. B. Williamson, Selby Haar, E. W. Stevenson, C. Fortescue, John J. Frank, J. M. Weed, Carl J. Fechheimer, Paul MacGahan, H. L. Wallau, A. Herz, D. W. Roper, Edmund C. Stone, C. P. Randolph, and E. D. Edmonston.

General remarks on relative merits of different methods of temperature measurement in connection with the rating of electrical machinery. Thermal data from experience with electrical machinery, apparatus and materials. Results of extensive tests on current-carrying capacity of different types of cables. Temperature rise calculations.

INDUCTION MOTOR LOAD LOSSES

Henry G. Reist and A. E. Averrett **Vol. xxxii—1913, pp. 433-438**

Discussion of the effect of load upon copper and core losses with different types of slot and winding construction, followed by tests and general conclusions as to effect of load losses.

Discussion under Group II.

STRAY LOSSES IN INDUCTION MOTORS

A. M. Dudley **Vol. xxxii—1913, pp. 439-454**

Discussion of load losses of induction motors of various sizes. Recommendations for standardization rules covering suggested method of determining load losses from no-load tests.

Discussion under Group II.

NOTES ON INDUCTION MOTOR LOSSES

R. W Davis **Vol. xxxii—1913, pp. 455-457**

Tabulated test results of stray losses in different sizes of induction motors.

Discussion under Group II.

DETERMINATION OF LOAD LOSS CORRECTION FACTORS FOR ROTATING ELECTRIC MACHINES

E. M. Olin and S. L. Henderson **Vol. xxxii—1913, pp. 479-502**

Description and results of tests on d.c. and a.c. generators and synchronous converters to determine load losses and fix a correction factor that can be used with no-load measurements to get the true losses under load. Results in tabular and graphic form. Correction factors for well designed d.c. generators and motors, synchronous generators and motors, 25 and 60-cycle synchronous converters.

Discussion under Group II.

LOAD LOSSES OF ALTERNATING-CURRENT GENERATORS

W. J. Foster and Edgar Knowlton **Vol. xxxii—1913, pp. 503-517**

Analytical discussion on load losses in a.c. generators and methods of determining them. Experimental investigation and comparison of various methods of measurement, including separation of losses, phase characteristic and circulating energy methods. Results in tabular and graphic form.

Discussion under Group II.

NOTES ON STRAY LOSSES IN SYNCHRONOUS MACHINES

F. K. Brainard **Vol. xxxii—1913, pp. 519-521**

Nature and determination of load losses in synchronous machines.

Discussion under Group II.

STRAY LOSS IN DIRECT-CURRENT COMMUTATING MACHINES

H. F. T. Erben and H. S. Page **Vol. xxxii—1913, pp. 523-529**

Description of method of testing machinery for load losses. Results of tests of number of a.c. machines given in form of loss-load curves.

Discussion under Group II.

THE DETERMINATION OF STRAY LOSSES FROM INPUT-OUTPUT TESTS

L. T. Robinson **Vol. xxxii—1913, pp. 531-550**

Analysis of factors that determine the precision of input-output efficiency tests. Tabulated results of a large number of tests to determine the degree of precision possible with commercial instruments and trained observers.

Discussion under Group II.

SOURCES OF ERROR IN THE EFFICIENCY DETERMINATION OF ROTATING ELECTRIC MACHINES

Elmer I. Chute and William Bradshaw **Vol. xxxii—1913, pp. 551-557**

Analytical discussion of errors due to instruments, observation and operating conditions. Comparison of input-output and separation of losses methods of determining efficiency.

Discussion under Group II.

BRUSH FRICTION AND CONTACT LOSSES

H. F. T. Erben and A. H. Freeman **Vol. xxxii—1913, pp. 559-564**

Experimental study of brush friction and contact resistance losses developing a practical method of calculation.

Discussion under Group II.

METHODS OF DETERMINING BRUSH LOSSES DUE TO CONTACT AND FRICTION

H. R. Edgecomb and W. A. Dick **Vol. xxxii—1913, pp. 565-576**

Analytical discussion of factors that enter into brush friction and contact resistance losses showing their relative importance. Supplemented by tests with special apparatus designed to furnish control of variable conditions.

Discussion under Group II.

COMMUTATION AND BRUSH LOSS

C. E. Wilson **Vol. xxxii—1913, pp. 577-584**

Experimental investigation and analysis of losses due to drop in brushes.

Discussion under Group II.

DISCUSSION GROUP II PAPERS

pp. 423-585

Methods of Determining Losses in Apparatus

(*a*) *Induction Motors*

Induction Motor Load Losses, by H. G. Reist, and A. E. Averrett.

Stray Losses in Induction Motors, by A. M. Dudley.

Notes on Induction Motor Losses, by R. W. Davis.

(b) Transformers

Losses in Transformers, by W. W. Lewis.

Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(c) Generators, A-C and D-C.

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.

Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.

Notes on Stray Losses in Synchronous Machines, by F. K. Brainard.

Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page.

(d) Errors of Tests

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson.

Sources of Error in the Efficiency Determination of Rotating Electric Machines, by Elmer I. Chute and William Bradshaw.

(e) Brush Losses

Brush Friction and Contact Losses, by H. F. T. Erben and A. H. Freeman.

Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.

Commutation and Brush Losses, by C. E. Wilson.

Discussion, pages 587-646, by Messrs. A. E. Averrett, B. A. Behrend, C. P. Steinmetz, James Burke, H. M. Hobart, Leo Schuler, B. G. Lamme, R. E. Hellmund, C. J. Fechheimer, Comfort A. Adams, R. B. Williamson, L. T. Robinson, M. G. Lloyd, J. M. Weed, C. Fortescue, E. A. Wagner, Charles F. Scott, J. E. Saunders, Paul M. Lincoln, W. C. Smith, G. K. Kaiser, W. B. Brady, A. H. Freeman, Alexander Gray, R. B. Treat, W. F. Dawson, F. D. Newbury, L. E. Underwood, T. M. McNiece, L. R. Berkeley and E. H. Martindale, John L. Harper, W. J. Foster, H. F. T. Erben, E. M. Olin and E. I. Chute.

Suggestions for terminology of load and stray losses. Definitions of core losses in induction motors and transformers. Determination of transformer losses. Effects of various factors upon brush friction. Care of commutators and brushes. Effect of brush angle inclination upon friction. Variation of friction with current density. Discussion of methods of measuring and estimating efficiency of generators and motors.

COMPARISON OF METHODS OF LOADING LARGE A-C. AND D-C. GENERATORS AND SYNCHRONOUS CONVERTERS FOR FACTORY TEMPERATURE TESTS

F. D. Newbury **Vol. xxxii—1913, pp. 649-665**

Classification and discussion of various methods of artificially loading rotating electrical machinery for operating temperature tests. Tests comparing various methods with actual energy load. Results tabulated.

Discussion under Group III.

COMPARISON OF METHODS OF MAKING LOAD TESTS ON A-C. GENERATORS AND ON INDUCTION MOTORS

E. F. Collins and W. E. Holcombe **Vol. xxxii—1913, pp. 667-681**

Brief description of most practical methods of obtaining normal load temperature in a.c. generators and induction motors under no-load and partial load conditions. Comparisons of results with actual full load tests. Results in tabular form.

Discussion under Group III.

NOTES ON METHODS OF MAKING LOAD TESTS ON LARGE INDUCTION MOTORS
A. M. Dudley **Vol. xxxii—1913, pp. 683-690**

Brief description and discussion of loading back and artificial loading tests for induction motors. Comparison of series of tests by circulating current method with actual load test. Results tabulated.

Discussion under Group III.

DISCUSSION GROUP III PAPERS
pp. 649-708

Method of Testing Apparatus for Performance

(*a*) *Generators and Induction Motors*

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests in A-C. Generators and on Induction Motors, by E. F. Collins and W. E. Holcombe.

Notes on Method of Making Load Tests on Large Induction Motors, by A. M. Dudley.

(*b*) *Transformers*

Load Tests on Transformers, by J. J. K. Madden.

Sources of Error in Transformer Tests, by W. M. McConahey and C. Fortescue.

Discussion, pages 711-729, by Messrs. A. E. Averrett, R. B. Williamson, R. E. Hellmund, B. G. Lamme, Leo Schuler, E. I. Chute, Paul M. Lincoln, F. D. Newbury, A. J. Porskievies, Alexander Gray, B. A. Behrend, H. M. Hobart, Stuart L. Henderson, J. J. K. Madden, Charles P. Steinmetz, W. J. Foster, Edgar Knowlton, C. J. Fechheimer, J. M. Weed and M. G. Lloyd.

General remarks and opinions on methods of loading generators, motors, and transformers artificially, based largely on experience. Suggested definition for transformer ratio.

POTENTIAL WAVES OF ALTERNATING-CURRENT GENERATORS
W. J. Foster **Vol. xxxii—1913, pp. 749-764**

Collection of e.m.f. wave shapes to show: first, the evolution of a.c. generators, second, the effect of load and no-load shapes; third, typical waves of machinery in extensive commercial service.

Discussion under Group IV.

THE EXPERIMENTAL DETERMINATION OF THE REGULATION OF ALTERNATORS
A. B. Field **Vol. xxxii—1913, pp. 783-78**

Criticisms of present Standardization Rules for specification and determination of regulation, followed by definite recommendations.

Discussion under Group IV.

REGULATION OF DEFINITE POLE ALTERNATORS
Soren H. Mortensen **Vol. xxxii—1913, pp. 789-794**

Description of method of determining regulation by Potier's triangle. Comparison of this method with Institute Rules method and with actual tests on a large number of three-phase, two-phase and single-phase machines. Results tabulated and saturation curves plotted for each method.

Discussion under Group IV.

GENERATOR AND PRIME MOVER CAPACITIES

David B. Rushmore and Eric A. Lof **Vol. xxxii—1913, pp. 798-804**

Brief review of relation between rating of steam and gas prime movers and generators to which they are connected. Discussion of selection of water wheel capacity with due regard for hydraulic as well as electrical load conditions. Efficiency curves of different types of prime movers.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M. Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, W. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave form measurement, test data. Calculation of alternator regulation and description of method.

OPERATION OF TRANSMISSION LINES

Lee Hagood **Vol. xxxii—1913, pp. 855-881**

Control of voltage and power factor in medium and high-tension transmission lines by means of synchronous machines. Examples showing methods of calculating the performance of the system and demonstrating the savings and improved service resulting from use of synchronous machines. Performance curves given for each transmission system discussed.

Discussion, pages 882-892, by Messrs. Herbert W. Crozier, Lee Hagood Robert Sibley, Professor Cory, L. P. Jorgensen, J. P. Jollyman, L. N. Peart, J. P. Francis, R. C. Powell, and H. Y. Hall.

General remarks on use of synchronous machines for transmission line regulation. Actual experience and tests from systems of operation.

ALTERNATING-CURRENT MOTORS FOR THE ECONOMIC OPERATION OF MINE FANS

F. B. Crosby **Vol. xxxii—1913, pp. 1073-1086**

Brief review of methods of varying speed of induction motors with special reference to regulating sets and commutating machines. Efficiency curves for different methods.

Discussion, pages 1087-1096, by Messrs. C. W. Beers, Wilfred Sykes, George R. Wood, H. C. Eddy, Graham Bright, H. Meyer-Delius, W. O. E. Schumann, B. M. Fast, H. L. Beach, and F. B Crosby.

General remarks on operation of mine fans and the use of regulator commutating machines with induction motors.

THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING

F. D. Newbury **Vol. xxxii—1913, pp. 1509-1525**

Analytical discussion of the starting performance of synchronous motors, started according to various commercial methods. Reasoning substantiated by actual tests. Starting characteristics plotted as curves for different conditions.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

COMMUTATING-POLE SATURATION IN D-C. MACHINES

Harold E. Stokes **Vol. xxxii—1913, pp. 1527-1543**

Adaptation of Gisbert Kapp's method of obtaining saturation in transformers to commutating poles under load. Description and method of test and calculation.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

ohn C. Parker **Vol. xxxii—1913, pp. 1559-1564**

Suitable uses for synchronous motors. Special adaptation of pumps and air compressors for favorable starting conditions.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

OPERATION OF FREQUENCY CHANGERS

N. E. Funk **Vol. xxxii—1913, pp. 1713-1730**

General review of theory of parallel operation of synchronous frequency changers. Detailed description of method of synchronizing with rotating synchroscope and a special synchronizing indicator. Examples of use of indicator.

Discussion (including that of papers by H. R. Summerhayes and B. G. Jamieson) pages 1731-1736, by Messrs. D. B. Rushmore, F. D. Newbury, F. C. Caldwell, Paul M. Lincoln, H. M. Hobart, Henry W. Peck, S. D. Sprong, H. R. Summerhayes, J. C. Lincoln, D. W. Roper and N. E. Funk.

General remarks on the advisability of running machinery unattended. Oil pressure for facilitating the starting of large machines.

INSTABILITY OF ELECTRIC CIRCUITS

Charles P. Steinmetz **Vol. xxxii—1913, pp. 2008-2031**

Analysis of transient, unstable equilibrium and permanently unstable conditions in electric circuits using practical examples of each to explain the principles involved. Electrical equilibrium as affected by switching, formation of arcs, unstable loading of induction motors, hunting of synchronous machines, etc. Equations for use in determination of synchronizing and damping powers in synchronous machines.

No discussion.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

Alfred E. Waller **Vol. xxxii—1913, pp. 2023-2036**

Consideration of some of the most important factors in the design of lighting equipment for motor cars. Brief description of different mechanical and electrical methods of controlling the output of the generator. More detailed description of a certain system using a shunt generator with a Tirrill regulator method of control.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

Alexander Churchward **Vol. xxxii—1913, pp. 2037-2041**

Advantages of constant-speed generator for battery charging and series motor for starting. Performance curves for battery charging and lighting under various conditions of car speed and battery charge for constant-speed generator. Also performance curves for variable-speed generators.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

Frank Conrad **Vol. xxxii—1913, pp. 2042-2051**

Description of constant-current generator system for ignition, lighting and starting. Description of ignition device, designed to vary angular time of contact with speed. Oscillograms of ignition current and curves of 4 and 6-cylinder motor torque.

Discussion (including that of papers by Alfred E. Waller and Alexander Churchward), pages 2052-2075, by Messrs. H. Ward Leonard, Leonard Kebler, Amon W. Copley, A. D. T. Libby, Harold Goodwin, Jr., C. E. Wilson, Benjamin F. Bailey, Kingston Forbes, Alexander Churchward, Alfred E. Waller, Frank Conrad, Alden L. McMurtry, Frederick S. Dellenbaugh, Jr., and John R. King.

Relative merits of constant-speed and variable-speed generators for motor car operation. Tests of efficiency of slipping clutch and bucking series coil. Relative advantages of various car wiring systems. Rosenberg dynamo for variable speed lighting.

10. PRIME MOVERS AND STEAM BOILERS

GENERATOR AND PRIME MOVER CAPACITIES

David B. Rushmore and Eric A. Lof **Vol. xxxii—1913, pp. 795-804**

Brief review of relation between rating of steam and gas prime movers and generators to which they are connected. Discussion of selection

of water wheel capacity with due regard for hydraulic as well as electrical load conditions. Efficiency curves of different types of prime movers.

Discussion under Group IV.

STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS

H. G. Stott and W. S. Gorsuch **Vol. xxxii—1913, pp. 1619-1651**

Detailed analysis of cost of energy production with a view of classifying items for intelligent comparison of one plant with another. Method of allowing for differences in wages, coal cost and load factor. Suggested forms for tabulating costs and depreciation.

Discussion, pages 1652-1683, by Messrs. Henry Floy, Carl Schwartz, William McClellan, C. O. Mailloux, Peter Junkersfeld, D. B. Rushmore, L. P. Crecelius, W. G. Carlton, August H. Kruesi, D. C. Jackson, Ralph D. Mershon, P. W. Sothman, H. M. Hobart, W. S. Gorsuch, E. D. Dreyfus, Charles S. Ruffner, and S. D. Sprong.

General remarks on methods of figuring costs and depreciation. Classification of accounts used by certain large corporations and societies. Methods of comparing costs of production in different plants.

POWER FROM MERCURY VAPOR

W. L. R. Emmet **Vol. xxxii—1913, pp. 2133-2149**

Exposition of a process of utilizing mercury vapor pressure in a turbine and then absorbing the exhaust heat in a steam boiler which serves as a condenser, the steam being used in the usual way. Theory of process and account of experimental investigation together with description of the mercury boiler construction.

No discussion.

11. CENTRAL STATIONS

PURCHASED POWER IN COAL MINES

H. C. Eddy **Vol. xxxii—1913, pp. 1029-1034**

Brief analysis of the advantages of central station supply over isolated plant.

Discussion incorporated with that of paper by C. W. Beers on "Central Station Power for Coal Mines."

CENTRAL STATION POWER FOR COAL MINES

C. W. Beers **Vol. xxxii—1913, pp. 1036-1048**

Advantages of central station supply from the coal miner's point of view. Analysis of fixed charges and operating costs for isolated mine power plant. Outline of power contract between central station company and coal mining company.

Discussion (including that of paper by H. C. Eddy), pages 1046-1053, by Messrs. K. A. Pauly, George H. Morse, E. D. Dreyfus, T. E. Tynes, W. Partridge, W. E. Dickinson, H. C. Eddy, George R. Wood and C. W. Beers.

General remarks on the purchase of central station energy for coal mines. Load factors and cost.

CENTRAL STATION POWER FOR MINES

J. S. Jenks **Vol. xxxii—1913, pp. 1097-1102**

Brief outline of development of supply of electric energy for mines by the West Penn system, describing the equipment, troubles encountered and how they were overcome.

Discussion incorporated with that of paper by Messrs. H. M. Warren and A. S. Biesecker on "Characteristics of Substation Loads at the Anthracite Collieries of the Lackawanna R. R. Co."

CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R. R. CO.

H. M. Warren and A. S. Biesecker **Vol. xxxii—1913, pp. 1103-1109**

Description of tests with results on 15 mine substations. Load curves and load factors.

Discussion (including that of paper by J. S. Jenks) pages 1110-1119, by Messrs. Graham Bright, W. A. Thomas, J. Paul Clayton, George R. Wood, H. M. Warren, George H. Morse, C. W. PenDell, P. M. Lincoln, Sidney G. Vigo, C. I. Weaver, and T. E. Tynes.

General remarks on rates and methods of charging for central station energy. Definition of load factor and effect on rates.

MINING LOADS FOR CENTRAL STATIONS

Wilfred Sykes and Graham Bright **Vol. xxxii—1913, pp. 1121-1136**

Classification of mining service and analytical discussion of power requirements and load characteristics of each type of service. Outline and discussion of various methods of charging for and measuring central station service. Suggestions for contracts.

Discussion, pages 1137-1147, by Messrs. P. M. Lincoln, Sidney G. Vigo, Theodore Swann, H. C. Eddy, and Graham Bright.

General remarks on methods of charging for central station service with illustrations from actual practice of large companies.

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

John C. Parker **Vol. xxxii—1913, pp. 1559-1564**

Suitable uses for synchronous motors. Special adaptation of pumps and air compressors for favorable starting conditions.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS

H. G. Stott and W. S. Gorsuch **Vol. xxxii—1913, pp. 1619-1651**

Detailed analysis of cost of energy production with a view to classifying items for intelligent comparison of one plant with another. Method of allowing for differences in wages, coal cost and load factor. Suggested forms for tabulating costs and depreciation.

Discussion, pages 1652-1683, by Messrs. Henry Floy, Carl Schwartz, William McClellan, C. O. Mailloux, Peter Junkersfeld, D. B. Rushmore, L. P. Crecelius, W. G. Carlton, August H. Kruesi, D. C. Jackson, Ralph D. Mershon, P. W. Sothman, H. M. Hobart, W.S. Gorsuch, E.D. Dreyfus, Charles S. Ruffner, and S. D. Sprong.

General remarks on methods of figuring costs and depreciation. Classification of accounts used by certain large corporations and societies. Methods of comparing costs of production in different plants.

RELATION OF PLANT SIZE TO POWER COST

P. M. Lincoln **Vol. xxxii—1913, pp. 1981-1992**

Superficial analysis of economic advantages of electric energy production in a central plant as compared with generation of energy for the same purposes in a number of small isolated plants, regarded from the standpoint of first cost, operating economy and load characteristics.

Discussion, pages 1993-2004, by Messrs. Harry Archer Hornor, W. C. L. Eglin, P. V. Stevens, C. O. Mailloux, M. G. Lloyd, J. P. Jackson, G. J. Blum and P. M. Lincoln.

Cases where isolated plant has marked advantage over central station supply.

FACTORS DETERMINING A REASONABLE CHARGE FOR PUBLIC UTILITY SERVICE

M. E. Cooley **Vol. xxxii—1913, pp. 2077-2095**

Clear exposition of the various elements that enter into the financing, organization, operation and insurance of a public service corporation or utility, tracing the steps taken and expenses incurred from its inception to its completion.

No discussion.

12. PARALLEL OPERATION

OPERATION OF FREQUENCY CHANGERS

N. E. Funk **Vol. xxxii—1913, pp. 1713-1730**

General review of theory of parallel operation of synchronous frequency changers. Detailed description of method of synchronizing with rotating synchroscope and a special synchronizing indicator. Examples of use of indicator.

Discussion (including that of papers by H. R. Summerhayes and B. G. Jamieson) pages 1731-1736, by Messrs. D. B. Rushmore, F. D. Newbury, F. C. Caldwell, Paul M. Lincoln, H. M. Hobart, Henry W. Peck, S. D. Sprong, H. R. Summerhayes, J. C. Lincoln, D. W. Roper and N. E. Funk.

General remarks on the advisability of running machinery unattended. Oil pressure for facilitating the starting of large machines.

13. TRANSMISSION LINES

OPERATION OF TRANSMISSION LINES

Lee Hagood **Vol. xxxii—1913, pp. 855-881**

Control of voltage and power factor in medium and high-tension transmission lines by means of synchronous machines. Examples showing methods of calculating the performance of the system and demonstrating the savings and improved results resulting from use of synchronous machines. Performance curves given for each transmission system discussed.

Discussion, pages 882-892, by Messrs. Herbert W. Crozier, Lee Hagood, Robert Sibley, Professor Cory, L. P. Jorgensen, J. P. Jollyman, L. N. Peart, J. P. Francis, R. C. Powell, and H. Y. Hall.

General remarks on use of synchronous machines for transmission line regulation. Actual experience and tests from systems of operation.

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE SUSPENSION INSULATORS

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1457-1461**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS

J. A Sandford, Jr. **Vol. xxxii—1913, pp. 1462-1470**

Discussion incorporated with that of paper by Percy H. Thomas on "Insulator Testing Specification for Insulators Having an Operating Voltage Exceeding 25,000 Volts."

INSULATOR TESTING SPECIFICATION FOR INSULATORS HAVING AN OPERATING VOLTAGE EXCEEDING 25,000 VOLTS

Percy H. Thomas **Vol. xxxii—1913, pp. 1471-1479**

Discussion (including that of papers by Messrs. F. W. Peek, Jr. and J. A. Sanford, Jr.,) pages 1480-1508, by Messrs. F. W. Peek, Jr., J. A. Sandford, Jr., P. H. Thomas, L. C. Nicholson, H. W. Crozier, H. Koganei, M. T. Crawford, C. O. Mailloux, Paul M. Lincoln, Hugh T. Wreaks, E. E. F. Creighton, Ralph D. Mershon, E. M. Hewlett, P. W. Sothman and C. F. Scott.

Criticisms and suggestions for specifications for the design and testing of insulators. Effect of simultaneous mechanical and electrical stresses, tests.

CONSTANT-VOLTAGE TRANSMISSION

H. B. Dwight **Vol. xxxii—1913, pp. 1548-1588**

Comparison of transmission line operation with voltage regulated at the generator and with voltage regulated at both generator and receiver. Analytical discussion of advantages and disadvantages of synchronous condensers and numerical examples of savings in 100-mile and 200-mile transmission lines. Results plotted as curves.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

THEORY OF THE NON-ELASTIC AND ELASTIC CATENARY AS APPLIED TO TRANSMISSION LINES

C. A. Pierce, F. J Adams and G. I. Gilchrest **Vol. xxxii—1913, pp. 1568-1581**

Mathematical development of catenary curve and deduction of simple equations for practical calculations. Experimental results compared with calculations by the author's method.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

THE ELECTRIC STRENGTH OF AIR—IV

J. B. Whitehead and T. T. Fitch **Vol. xxxii—1913, pp. 1737-1753**

Description of tests and apparatus and discussion of results of a series of investigations on the effects of pressure, temperature and density upon the formation of corona. Results tabulated and plotted as curves Review of earlier work on corona. Application of ionization theory to corona formation. Bibliography of corona and dielectric strength of air.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

F. W. Peek, Jr. **Vol. xxxii—1913, pp. 1767-1788**

Experimental investigation and development of the laws of corona formation and rupture gradient of air or gas including effects of temperature, density, pressure above and below atmosphere, spacing, etc. Tests on rods and spheres. Results tabulated and plotted as curves. Equations given for calculation of gradient between rods and between spheres. Rupture explained both by critical energy and by ionization.

Discussion incorporated with that of paper by Edward Bennett on "An Oscillograph Study of Corona."

AN OSCILLOGRAPH STUDY OF CORONA

Edward Bennett **Vol. xxxii—1913, pp. 1787-1809**

Experimental investigation of corona by means of oscillographs of the charging current to a conductor producing corona. Description of method and apparatus for making the oscillograms. Oscillograms of charging current over a range of e.m.f. above and below corona e.m.f. with a detailed study and searching analysis of each curve.

Discussion, (including that of papers by Messrs. J. B. Whitehead and T. T. Fitch, W. W. Strong, and F. W. Peek, Jr.) pages 1810-1828, by Messrs. C. F. Scott, L. T. Robinson, J. B. Whitehead, Alan E. Flowers, F. W. Peek, Jr., J. B. Taylor, W. H. Pratt, P. M. Lincoln, Edward Bennett, William J. Hammer, and Harris J. Ryan.

General remarks on corona—investigations and experiences. Use of corona for e.m.f. measurement. Measurement of e.m.f. independent of frequency. D-c. corona. Effect of frequency upon corona losses.

EFFECTS OF ICE LOADING ON TRANSMISSION LINES

V. H. Greisser **Vol. xxxii—1913, pp. 1839-1844**

Account of actual experience with ice coatings and experimental investigation with artificial loads similar in magnitude and distribution to those observed in actual service on a suspension insulator line of the Washington Water Power Company, Spokane. Sags and rises plotted as curves for different loadings. Suggested construction to prevent damage and short-circuits.

No discussion.

15. DISTRIBUTION SYSTEMS

CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R. R. CO.

H. M. Warren and A. S. Biesecker **Vol. xxxii—1913, pp. 1105-1109**

Description of tests with results on 15 mine substations. Load curves and load factors.

Discussion (including that of paper by J. S. Jenks) pages 1110-1119, by Messrs. Graham Bright, W. A. Thomas, J. Paul Clayton, George R. Wood, H. M. Warren, George H. Morse, C. W. PenDell, P. M. Lincoln, Sidney G. Vigo, C. I. Weaver, and T. E. Tynes.

General remarks on rates and methods of charging for central station energy. Definition of load factor and effect on rates.

TRUNK LINE ELECTRIFICATION

Charles P. Kahler **Vol. xxxii—1913, pp. 1189-1226**

Detailed and comprehensive analysis of the economics of railroad electrification with well digested data from actual practice. Example of heavy electrification worked out and all items tabulated for easy reference and results derived which determine the actual return on the investment, everything taken into consideration. Effect of substitution of electric motive power for steam upon railroad operation. Comparative cost of operation by steam and electricity.

Discussion (including that of paper by H. M. Hobart), pages 1227-1260, by Messrs. A. H. Armstrong, F. E. Wynne, George Hill, W. S. Murray, A. H. Babcock, H. Y. Hall and G. W. Welsh, F. W. Carter, F. C. Merriell, H. F. Parshall, Charles P. Kahler, Roger T. Smith and H. M. Hobart.

General remarks on the economics of railroad electrification. D-c. vs. a-c. electrification. Possibilities of mercury rectifiers in railroad work. Comparison of steam and electric locomotives for a given service. Cost of distribution system and steam and electric locomotives. Cost data and other assumptions used for comparing steam with electricity given in full.

THEORY OF THE NON-ELASTIC AND ELASTIC CATENARY AS APPLIED TO TRANSMISSION LINES

C. A. Pierce, F. J. Adams and G. I. Gilchrest **Vol. xxxii—1913, pp. 1543-1581**

Mathematical development of catenary curve and deduction of simple equations for practical calculations. Experimental results compared with calculations by the author's method.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

AUTOMATIC SUBSTATIONS

H. R. Summerhayes **Vol. xxxii—1913, pp. 1685-1696**

Brief review of well-known applications of remote control of electrical apparatus and machinery. Description of remote controlled synchronous converter substation of Detroit Edison Company—installation, operation and protection.

Discussion incorporated with that of paper by N. E. Funk on "Operation of Frequency Changers."

CONVERTING SUBSTATIONS IN BASEMENTS AND SUB-BASEMENTS

B. G. Jamieson **Vol. xxxii—1913, pp. 1699-1711**

Discussion of difficulties encountered in the construction and operation of underground converter and battery substations based on experience in Chicago. Methods of construction and suggestions for improved apparatus.

Discussion incorporated with that of paper by N. E. Funk on "Operation of Frequency Changers."

A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT

John B. Fisken **Vol. xxxii—1913, pp. 1891-1902**

Description of construction and equipment of a portable or "take-down" substation for mountainous districts. Description of water relay for transformer protection. Cost of construction and operation.

Discussion, pages 1903-1912, by Messrs. W. V. Hunt, Frederick D. Nims, W. Fraser, C. F. Terrell, L. G. Robinson, J. A. Lighthipe, A. A. Miller, R. W. Pope, R. F. Hayward, V. Karapetoff and John B. Fisken.

General remarks on construction, equipment and operation of portable and automatic substations.

INDUSTRIAL SUBSTATIONS

H. P. Liversidge **Vol. xxxii—1913, pp. 1968-1974**

Outline of development of the substation as a part of the distribution system. Brief description of a series of industrial substations with circuit diagrams and layouts, dwelling upon the important characteristics of design and general construction.

Discussion, pages 1975-1979, by Messrs. W. C. L. Eglin, P. M. Lincoln, John Mathews, G. W. Brooks, P. V. Stephens, Charles Penrose, Harold Goodwin, Jr., and H. P. Liversidge.

General comments upon substation design.

16. CONTROL, REGULATION AND SWITCHING

RATING OF OIL CIRCUIT BREAKERS WITH REFERENCE TO RUPTURING CAPACITY

George A. Burnham **Vol. xxxii—1913, pp. 731-732**

Suggestions for Standard Committee.

Discussion under Group IV.

DISCUSSION GROUP IV PAPERS

pp. 731-804

Miscellaneous Subjects Relating to Rating

(*a*) *Oil Switches*

Rating of Oil Circuit Breakers with reference to Rupturing Capacity, by G. A. Burnham.

(*b*) *Spark Gap*

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere-Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(*c*) *Wave Form*

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effect on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(*d*) *Regulation*

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

Discussion, pages 807-854, by Messrs. Paul M. Lincoln, M. G. Lloyd, F. D. Newbury, Ford W. Harris, Chester Lichtenberg, F. W. Peek, Jr., C. E. Skinner, J. A. Sandford, Jr., Comfort A. Adams, L. W. Chubb, Percy H. Thomas, C. Fortescue, M. W. Franklin, Charles P. Steinmetz, J. B. Whitehead, F. M. Farmer and E. D. Doyle, B. G. Lamme, A. E. Kennelly, Charles F. Scott, L. T. Robinson, Taylor Reed, Cassius M.

Davis, S. S. Seyfert, Alexander Gray, Frank T. Leilich, L. L. Waters, George Smith, C. J. Fechheimer and Leo Schuler.

General remarks, criticisms and suggestions. Test data, calibration curves and laws of sphere-gap voltmeter. Wave-form measurement, test data. Calculation of alternator regulation and description of method.

OPERATION OF TRANSMISSION LINES

Lee Hagood — **Vol. xxxii—1913, pp. 886-881**

Control of voltage and power factor in medium and high-tension transmission lines by means of synchronous machines. Examples showing methods of calculating the performance of the system and demonstrating the savings and improved service resulting from use of synchronous machines. Performance curves given for each transmission system discussed.

Discussion, pages 882-892, by Messrs. Herbert W. Crozier, Lee Hagood, Robert Sibley, Professor Cory, L. P. Jorgensen, J. P. Jollyman, L. N. Peart, J. P. Francis, R. C. Powell, and H. Y. Hall.

General remarks on use of synchronous machines for transmission line regulation. Actual experience and test from systems of operation.

SAFEGUARDING THE USE OF ELECTRICITY IN MINES

H. H. Clark — **Vol. xxxii—1913, pp. 1058-1062**

Analysis of accidents caused by electricity and the factors that determine the risk. Directions for reducing and preventing such accidents. Effect of electrical operation in reducing the usual run of accidents in mines.

Discussion, pages 1063-1071, by Messrs. C. A. Lauffer, J. S. Jenks, Ralph D. Mershon, George R. Wood, Graham Bright, W. E. Dickinson, Wilfred Sykes, L. R. Palmer and Harold H. Clark.

General remarks on electrical accidents in mines. Directions for resuscitation by the Schafer prone pressure method. Statistics on mine accidents.

CONSTANT-VOLTAGE TRANSMISSION

H. B. Dwight — **Vol. xxxii—1913, pp. 1545-1588**

Comparison of transmission line operation with voltage regulated at the generator and with voltage regulated at both generator and receiver. Analytical discussion of advantages and disadvantages of synchronous condensers and numerical examples of savings in 100-mile and 200-mile transmission lines. Results plotted as curves.

Discussion incorporated with that of paper by C. A. Kelsey on "Electrical Requirements of Certain Machines in the Rubber Industry."

AUTOMATIC SUBSTATIONS

H. R. Summerhayes — **Vol. xxxii—1913, pp. 1685-1698**

Brief review of well-known applications of remote control of electrical apparatus and machinery. Description of remote controlled synchronous converter substation of Detroit Edison Company—installation, operation and protection.

Discussion incorporated with that of paper by N. E. Funk on "Operation of Frequency Changers."

A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT

John B. Fisken **Vol. xxxii—1913, pp. 1891-1902**

Description of construction and equipment of a portable or "take-down" substation for mountainous districts. Description of water relay for transformer protection. Cost of construction and operation.

Discussion, pages 1903-1912, by Messrs. W. V. Hunt, Frederick D. Nims, W. Fraser, C. F. Terrill, L. G. Robinson, J. A. Lighthipe, A. A. Miller, R. W. Pope, R. F. Hayward, V. Karapetoff and John B. Fisken.

General remarks on construction, equipment and operation of portable and automatic substations.

17. TRACTION

2400-VOLT RAILWAY ELECTRIFICATION

H. M. Hobart **Vol. xxxii—1913, pp. 1139-1188**

Comparison of the cost of operation of high-tension electric systems with steam. Numerical examples worked out in detail for various classes of railroad service and results discussed. Methods of calculation given and results tabulated.

Discussion incorporated with that of paper by Charles P. Kahler on "Trunk Line Electrification."

TRUNK LINE ELECTRIFICATION

Charles P. Kahler **Vol. xxxii—1913, pp. 1189-1226**

Detailed and comprehensive analysis of the economics of railroad electrification with well digested data from actual practice. Example of heavy electrification worked out and all items tabulated for easy reference and results derived which determine the actual return on the investment. Everything taken into consideration. Effect of substitution of electric motive power for steam upon railroad operation. Comparative cost of operation by steam and electricity.

Discussion (including that of paper by H. M. Hobart), pages 1227-1260, by Messrs. A. H. Armstrong, F. E. Wynne, George Hill, W. S. Murray, A. H. Babcock, H. Y. Hall and G. W. Welsh, F. W. Carter, F. C. Merriell, H. F. Parshall, Charles P. Kahler, Roger T. Smith and H. M. Hobart.

General remarks on the economics of railroad electrification. D-c. vs. a-c. electrification. Possibilities of mercury rectifiers in railroad work. Comparison of steam and electric locomotives for a given service. Cost of distribution system and steam and electric locomotives. Cost data and other assumptions used for comparing steam with electricity given in full.

ELECTROLYTIC CORROSION OF IRON IN SOILS

Burton McCollum and K. H. Logan **Vol. xxxii—1913, pp. 1345-1403**

Experimental investigation of electrolysis of iron in soil from various cities taking up each variable factor separately and determining its influence upon corrosion. Effect of current density, moisture, temperature, depth of burial, oxygen, kind of iron, chemicals in soil, etc. upon corrosion efficiency. Experimental study of earth resistance and the factors that affect it. Detailed description of tests and tabulation of results.

Discussion, pages 1404-1412, by Messrs. J. L. R. Hayden, Alexander Maxwell, D. C. Jackson, Hugh T. Wreaks, Harold V. Bozell, Harry

Barker, F. C. Caldwell, J. C. Lincoln, Henry G. Stott, Albert F. Ganz, and Burton McCollum.

General remarks on electrolysis from street railway currents and its prevention.

MOUNTAIN RAILWAY ELECTRIFICATION

Allen H. Babcock **Vol. xxxii—1913, pp. 1848-1878**

Detailed description of a report on the problem of electrification going very thoroughly into the question of construction and operation costs for the electric system and the corresponding cost for steam. Assumptions and methods of estimates fully given. Complete cost figures in tabular form. Study of economical spacing of substations with results plotted as curves.

No discussion.

18. LIGHTING AND LAMPS

TUNGSTEN LAMPS OF HIGH EFFICIENCY

Irving Langmuir **Vol. xxxii—1913, pp. 1913-1933**

Experimental investigation of the causes of blackening. Detailed analysis of the various elements of the lamp as sources of gas and description of the effect of the various gases upon the performance of the lamp. Development of preventative measures.

Discussion incorporated with that of paper by Messrs. Irving Langmuir and J. A. Orange on "Tungsten Lamps of High Efficiency."

TUNGSTEN LAMPS OF HIGH EFFICIENCY

Irving Langmuir and J. A. Orange **Vol. xxxii—1913, pp. 1934-1946**

Description of design, construction and performance of nitrogen-filled lamps.

Discussion (including that of paper by Irving Langmuir) pages 1947-1954, by Messrs. John B. Taylor, John W. Howell, Farley Osgood, J. E. Randall, William McClellan, Irving Langmuir, John W. Lieb, Jr., M. G. Lloyd, and H. M. Fales.

Blackening of lamps. Advantages of nitrogen lamp in projection lantern work. Relative economy of incandescent lamps on basis of filament temperature.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

Alfred E. Waller **Vol. xxxii—1913, pp. 2025-2036**

Consideration of some of the most important factors in the design of lighting equipment for motor cars. Brief description of different mechanical and electrical methods of controlling the output of the generator. More detailed description of a certain system using a shunt generator with a Tirrill regulator method of control.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

Alexander Churchward **Vol. xxxii—1913, pp. 2037-2041**

Advantages of constant-speed generator for battery charging and series motor for starting. Performance curves for battery charging and light-

ing under various conditions of car speed and battery charge for constant-speed generator. Also performance curves for variable-speed generators.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

Frank Conrad **Vol. xxxii—1913, pp. 2042-2051**

Description of constant-current generator system for ignition, lighting and starting. Description of ignition device, designed to vary angular time of contact with speed. Oscillograms of ignition current and curves of 4 and 6-cylinder motor torque.

Discussion (including that of papers by Alfred E. Waller and Alexander Churchward), pages 2052-2075, by Messrs. H. Ward Leonard, Leonard Kebler, Almon W. Copley, A. D. T. Libby, Harold Goodwin, Jr., C. E. Wilson, Benjamin F. Bailey, Kingston Forbes, Alexander Churchward, Alfred E. Waller, Frank Conrad, Alden L. McMurtry, Frederick S. Dellenbaugh, Jr. and John R. King.

Relative merits of constant-speed and variable-speed generators for motor car operation. Tests of efficiency of slipping clutch and bucking series coil. Relative advantages of various car wiring systems. Rosenberg dynamo for variable speed lighting.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

PURCHASED POWER IN COAL MINES

H. C. Eddy **Vol. xxxii—1913, pp. 1029-1034**

Brief analysis of the advantages of central station supply over isolated plant.

Discussion incorporated with that of paper by C. W. Beers on "Central Station Power for Coal Mines."

CENTRAL STATION POWER FOR COAL MINES

C. W. Beers **Vol. xxxii—1913, pp. 1035-1045**

Advantages of central station supply from the coal miner's point of view. Analysis of fixed charges and operating costs for isolated mine power plant. Outline of power contract between central station company and coal mining company.

Discussion (including that of paper by H. C. Eddy), pages 1046-1053, by Messrs. K. A. Pauly, George H. Morse, E. D. Dreyfus, T. E. Tynes, W. Partridge, W. E. Dickinson, H. C. Eddy, George R. Wood and C. W. Beers.

General remarks on the purchase of central station energy for coal mines. Load factors and cost.

SAFEGUARDING THE USE OF ELECTRICITY IN MINES

H. H. Clark **Vol. xxxii—1913, pp. 1054-1062**

Analysis of accidents caused by electricity and the factors that determine the risk. Directions for reducing and preventing such accidents. Effect of electrical operation in reducing the usual run of accidents in mines

Discussion, pages 1063-1071, by Messrs. C. A. Lauffer, J. S. Jenks, Ralph D. Mershon, George R. Wood, Graham Bright, W. E. Dickinson, Wilfred Sykes, L. R. Palmer and Harold H. Clark.

General remarks on electrical accidents in mines. Directions for resuscitation by the Schafer prone pressure method. Statistics on mine accidents.

ALTERNATING-CURRENT MOTORS FOR THE ECONOMIC OPERATION OF MINE FANS

F. B. Crosby **Vol. xxxii—1913, pp. 1073-1086**

Brief review of methods of varying speed of induction motors with special reference to regulating sets and commutating machines. Efficiency curves for different methods.

Discussion, pages 1087-1096, by Messrs. C. W. Beers, Wilfred Sykes, George R. Wood, H. C. Eddy, Graham Bright, H. Meyer-Delius, W. O. E Schumann, B. M. Fast, H. L. Beach, and F. B. Crosby.

General remarks on operation of mine fans and the use of regulator commutating machines with induction motors.

CENTRAL STATION POWER FOR MINES

J. S. Jenks **Vol. xxxii—1913, pp. 1097-1102**

Brief outline of development of supply of electric energy for mines by the West Penn system, describing the equipment, troubles encountered and how they were overcome.

Discussion incorporated with that of paper by Messrs. H. M. Warren and A. S. Biesecker on "Characteristics of Substation Loads at the Anthracite Collieries of the Lackawanna R. R. Co."

CHARACTERISTICS OF SUBSTATIONS LOAD AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R. R. CO.

H. M. Warren and A. S. Biesecker **Vol. xxxii—1913, pp. 1103-1109**

Description of tests with results on 15 mine substations. Load curves and load factors.

Discussion (including that of paper by J. S. Jenks) pages 1110-1119, by Messrs. Graham Bright, W. A. Thomas, J. Paul Clayton, George R, Wood, H. H. Warren, George H. Morse, C. W. PenDell, P. M. Lincoln, Sidney G. Vigo, C. I. Weaver, and T. E. Tynes.

General remarks on rates and methods of charging for central station energy. Definition of load factor and effect on rates.

MINING LOADS FOR CENTRAL STATIONS

Wilfred Sykes and Graham Bright **Vol. xxxii—1913, pp. 1121-1136**

Classification of mining service and analytical discussion of power requirements and load characteristics of each type of service. Outline and discussion of various methods of charging for and measuring central station service. Suggestions for contracts.

Discussion, pages 1137-1147, by Messrs. P. M. Lincoln, Sidney G. Vigo, Theodore Swann, H. C. Eddy, and Graham Bright.

General remarks on methods of charging for central station service with illustrations from actual practice of large companies.

ELECTRICAL REQUIREMENTS OF CERTAIN MACHINES IN THE RUBBER INDUSTRY

C. A. Kelsey **Vol. xxxii—1913, pp. 1383-1388**

Brief description of some of the principal machines in the rubber mill and their power requirements.

Discussion (including that of papers by F. D. Newbury, Harold E. Stokes, H. B. Dwight, John C. Parker and Messrs. C. A. Pierce, F. J. Adams and G. I. Gilchrest), pages 1589-1618, by Messrs. William J. Foster, August H. Kruesi, F. D. Newbury, H. M. Hobart, J. M. Hipple, H. E Stokes, R. B. Williamson, Lee Hagood, N. E. Funk, M. T. Crawford, Henry W. Peck, F. C. Caldwell, Burton McCollum, H. B. Dwight, J. C. Lincoln, M. O. Dell Plain, C. P. Steinmetz, W. L. Merrill, H. H. Dewey, J. H. Wilson and C. J. Fechheimer.

General remarks on the use and characteristics of the synchronous motor. Performance of self-starting synchronous motors—experience and tests. Salient pole vs. round type. Value of power-factor regulation.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

Alfred E. Waller **Vol. xxxii—1913, pp. 2033-2038**

Consideration of some of the most important factors in the design of lighting equipment for motor cars. Brief description of different mechanical and electrical methods of controlling the output of the generator. More detailed description of a certain system using a shunt generator with a Tirrill regulator method of control.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

Alexander Churchward **Vol. xxxii—1913, pp. 2037-2041**

Advantages of constant-speed generator for battery charging and series motor for starting. Performance curves for battery charging and lighting under various conditions of car speed and battery charge for constant-speed generator. Also performance curves for variable-speed generators.

Discussion incorporated with that of paper by Frank Conrad on "Electrical Equipment of Gasoline Automobiles."

ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

Frank Conrad **Vol. xxxii—1913, pp. 2043-2051**

Description of constant-current generator system for ignition, lighting and starting. Description of ignition device, designed to vary angular time of contact with speed. Oscillograms of ignition current and curves of 4 and 6-cyclinder motor torque.

Discussion (including that of papers by Alfred E. Waller and Alexander Churchward), pages 2052-2075, by Messrs. H. Ward Leonard, Leonard Kebler, Almon W. Copley, A. D. T. Libby, Harold Goodwin, Jr., C. E. Wilson, Benjamin F. Bailey, Kingston Forbes, Alexander Churchward, Alfred E. Waller, Frank Conrad, Alden L. McMurtry, Frederick S. Dellenbaugh, Jr., and John R. King.

Relative merits of constant-speed and variable-speed generators for motor car operation. Tests of efficiency of slipping clutch and bucking series coil. Relative advantages of various car wiring systems. Rosenberg dynamo for variable speed lighting.

21. TELEPHONY AND TELEGRAPHY

TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND

A. E. Kennelly and F. W. Lieberknecht — **Vol. xxxii—1913, pp. 1283-1303**

Detailed description and a series of tests on a very long artificial telephone line. E.m.f. and current being measured both as to phase and amplitude. Results tabulated and plotted as vector diagrams. Bibliography of articles of measurement on artificial telephone lines and allied topics.

Discussion incorporated with that of paper by Messrs. H. M. Friendly and A. E. Burns on "Automatic Methods in Long Distance Telephone Operation."

AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION

H. M Friendly and A. E. Burns — **Vol. xxxii—1913, pp. 1305-1333**

Description of equipment and operation of long distance automatic system of the Northwestern Long Distance Telephone Company.

Discussion (including that of paper by Messrs. A. E. Kennelly and F. W. Lieberknecht), pages 1333-1334, by Messrs. F. K. Vreelnad, E. H. Colpitts, D. C. Jackson, George A. Campbell, R. S. Brown, J. B. Taylor, H. M. Friendly and Oberlin Smith.

Telephone line calculations. Definitions of iterative impedance and propagation constants. Use of integraph in solving equations.

THE GULF OF GEORGIA SUBMARINE TELEPHONE CABLE

E. P. LaBelle and L. P. Crim — **Vol. xxxii—1913, pp. 1877-1889**

Specifications for submarine cable load by Krarup system. Account of laying, splicing, locating faults, etc. Krarup continuous system compared with the Pupin coil system of loading.

No discussion.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

SAFEGUARDING THE USE OF ELECTRICITY IN MINES

H. H. Clark — **Vol. xxxii—1913, pp. 1058-1062**

Analysis of accidents caused by electricity and the factors that determine the risk. Directions for reducing and preventing such accidents. Effect of electrical operation in reducing the usual run of accidents in mines.

Discussion, pages 1063-1071, by Messrs. C. A. Lauffer, J. S. Jenks, Ralph D. Mershon, George R. Woods, Graham Bright, W. E. Dickinson, Wilfred Sykes, L. R. Palmer and Harold H. Clark.

General remarks on electrical accidents in mines. Directions for resuscitation by the Schafer prone pressure method. Statistics on mine accidents.

SOME ASPECTS OF INSTITUTE AFFAIRS

[President's Address]

Ralph D. Mershon — **Vol. xxxii—1913, pp. 1261-1270**

Criticisms of certain past practices and tendencies in the conduct of Institute affairs and suggestions for improvement by interesting a greater number of the membership at large in the oganization and its work.

No discussion.

A SUGGESTION FOR THE ENGINEERING PROFESSION

William McClellan **Vol. xxxii—1913, pp. 1271-1274**

Outline of a plan for merging all engineering societies into a federation with a pro-rata representation in the Government of a body devoted to general engineering of the broadest kind. Character of membership and scope of such a society briefly suggested.

Discussion pages 1275-1281, by Messrs. C. O. Mailloux, Oberlin Smith, Chas. L. Clarke, D. B. Rushmore, C. L. deMuralt and D. C. Jackson.

General remarks on the desirability and method of organizing a national and general engineering society.

FACTORS DETERMINING A REASONABLE CHARGE FOR PUBLIC UTILITY SERVICE

M. E. Cooley **Vol. xxxii—1913, pp. 2077-2095**

Clear exposition of the various elements that enter into the financing, organization, operation and insurance of a public service corporation or utility, tracing the steps taken and expenses incurred from its inception to its completion.

No discussion.

POWER FROM MERCURY VAPOR

W. L. R. Emmet **Vol. xxxii—1913, pp. 2133-2149**

Exposition of a process of utilizing mercury vapor pressure in a turbine and then absorbing the exhaust heat in a steam boiler which serves as a condenser, the steam being used in the usual way. Theory of process and account of experimental investigation together with description of the mercury boiler construction.

No discussion.

THE I. E. C. MEETING AT BERLIN

Advance Report To the U. S. National Committee on the Berlin Meeting of the International Electrotechnical Commission.

Vol. xxxii—1913, pp 2151-2165

Outline of results of Congress.

Appendix A—Report of Committee on Symbols.

Appendix B—Limits of observable temperatures adopted by the International Electrotechnical Commision, Sept. 1913.

Appendix C—Report of the National Laboratories concerning an international standard for copper.

No discussion.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1913.

Vol. xxxii—1913, pp. 2167-2192

TOPICAL INDEX

Abbreviations, standard 2163
Accidents, electrical, in mines 1055
mines, reduction by electricity 1061
statistics 1070
Accounts, classification, central station. (See Central Stations)
power plant. (See Power Plants)
Actinium, disintegration products 983
stages 983
Additional losses. (See Losses, extra)
Adhesion coefficient, railroad practice 1253
Air, conductivity, heat 304
corona. (See Corona)
dielectric strength 893 1737
bibliography 1753
effect of density 1768
electrode area, test 2107
hot furnace gases 1759
pressure 1737
temperature 1737
energy theory 1768
test 1769
law 1767
low air densities 1772
maximum gradient, formula 1767
rupturing energy 1768
test 2106
thin films 1771
electric breakdown 2112
insulating qualities, investigation 893
resistivity, heat 304
Aluminum paint, heat emissivity 310
American Society of Civil Engrs., part in engineering development 1279
Amortization Fund, calculation 1633
definition 1631
Apprenticeship schools. (See Education)
Arc, constant-potential, instability 2009
mercury, vapor, instability 2009
short-circuit, transmission line, characteristic 2011
Argon, effect on tungsten lamp performance 1924
Armature coil, heat flow 83
temperature distribution 84
magnetic testing, exploring coil calculation 1529
Asbestos, safe temperature, I. E. C. rules 2163
Ash handling machinery, cost 1038
Atom, average life 995
electric model 1007
Automobiles. (See Motor Cars.)
Avogadro's law 1749
Bakelite, conductivity, heat 303
resistivity, heat 303

Batteries, storage, cost 1893
life 1632
motor car lighting 2032
scrap value 1632
Battery-station, underground 1706
Bearings, oil pressure, to help starting 1736
safe temperature, I. E. C. rules 2163
temperature limit 135
Becquerel rays, discovery 954
Bell Telephone Co., Philadelphia, vocational instruction 1432
Bibliography, corona 1753
dielectric strength of air 1753
heat dissipation 313
references, on catenary, calculation 1581
Rosenburg generator 2074
telephone line measurements 1303
wave propagation over conductors 1303
Black body radiation 1010
Boiler-room, costs, classification 1623 1627
labor, cost 1657
Boilers, coal mine, loss 1036
cost 1038
effect of size 1983
fuel, figure of merit, definition 1648
installed, cost 1863
life 1632
mercury, vapor, construction 2144
setting 2146
rating in myriawatts 414
scrap value 1632
stokers, effect on cost of operation 1657
Boiling point, various materials. (See name of Material)
Bonding. (See Tracks.)
Bonds. (See Tracks).
Booster, synchronous, for e.m.f. compensation 878
wiring diagram 879
Brass, conductivity, heat 303
resistivity, heat 303
Bridges, steel, depreciation 1211
Brushes, contact resistance, determination 565
test methods 579
variation with temperature 563
various current densities 562
types 562
equation, effect of current density 618
friction 559
coefficient, variation with speed 563
determination 565
effect of angle 560 616
current 609 610
temperature 618
electrical measurement 572
equations 617
experimental investigation 610
factors that influence 573
measurement 571
mechanical measurement 572
recommendation for standardization rules 564
high resistance, value 581
losses (Also see Losses)
influence of current direction 613
Buildings, life 1632
scrap value 1632

Bushings. (Also see Insulators).
condenser type ... 904
wall, high tension ... 1894
Butte, Anaconda & Pacific R. R., electrification ... 1162
Cables, conductor temperature rise equation ... 327
current capacity, calculation, accuracy ... 344
effect of diameter ... 326
equation ... 342
general formula ... 347
density ... 350
rating ... 325
heating ... 333
rates, calculation ... 351
high-tension, limiting temperature ... 403
insulation, limiting temperature ... 403
iron, cost ... 1865
overload capacity ... 330
rubber insulated, current density ... 350
single-conductor, cambric insulated, leaded and braided,
current capacity, table ... 346
current-carrying capacity, table ... 387
rubber insulated, current capacity, table ... 345
steel, cost ... 1865
subway construction, manhole spacing ... 407
telephone, coil-loaded, advantages ... 1888
examples ... 1886
continuous loading system ... 1886
advantages ... 1889
Gulf of Georgia ... 1877
Krarup loading system ... 1883
splicing ... 1885
submarine, capacity ... 1879
insulation resistance ... 1879
laying ... 1877
location of faults ... 1887
mechanical properties ... 1879
protective apparatus ... 1882
resistance ... 1879
specifications ... 1879
temperature rise ... 391 392
three-conductor, current-carrying capacity, table ... 389
overload capacity ... 330
varnished cambric insulated, current density ... 350
Calorite, conductivity, heat ... 303
resistivity, heat ... 303
Cambric, varnished, conductivity, heat ... 303
dielectric strength, effect of electrode area,
moist air, test ... 2103
effect of electrode diameter 2099
in oil, test ... 2104
moist air, test ... 2103
resistivity, heat ... 303–340 357
Capacity, electric, cloth, measurement ... 2119
factor, definition ... 1669
effect on cost of energy production ... 1669
Capital expenses ... 2086
Carbon dioxide, effect on tungsten lamp performance ... 1923
monoxide, effect on tungsten lamp performance ... 1923
Cars, railroad, coal, repairs, cost ... 1212
freight, depreciation ... 1220
repairs, cost ... 1212
motor, cost ... 1209
depreciation ... 1212

Cars, railroad, motor (*continued*)
repair, cost 1219
passenger, depreciation 1220
repairs, cost 1212
Catenary, bibliographical references 1581
elastic, theory 1565
equations 1566
non-elastic, theory 1565
Cathode particles, definition 970
measurements 958
velocity measurement 959
rays, characteristics 990
Cellulose insulation, safe temperature 26
Cement insulator, moisture-proof 1481
specifications 1457 1481
Central stations. (Also see Public Utility).
administration expenses, classification 1636
items, definition 1637
amortization, calculation 1633
coal mine service, history 1097
contracts for mines, suggestions 1136
penalty for delays 1052
cost, classification 1659–1664 1680
comparison method 1649–1661 1676
items definition 1623
of energy production, standardization of method 1619
standardization, desirability 1663
energy production, cost, classification 1620
repairs, classification 1620
investment charges, definition 1629
operation, cost, effect of load-factor 1644
point of view compared with public 2081
rates. (See Rates).
saving by concentration 1984
supply disadvantages 1991 1993
effect of employers liability 1033
for coal mines 1029
sugar refining establishment, requirements 1998
use of synchronous motors 1559
vs. isolated plant for coal mines 1046
Charging current. (See Current).
Cinders, resistance, electric, tests 1399 1400
Circuit breakers. (See Switches).
Circuits, electric, instability 2005
continuous discharges 2012
hunting synchronous machines 2014
permanent instability 2010
transient disturbances 2005
unstable equilibrium 2006
Clay, resistance, electric, tests 1399 1400
Cloth, dielectric strength, testing apparatus 2119
empire, conductivity, heat 156 303
resistivity, heat 303
insulating, dielectric strength, test 2099
power, testing apparatus 2119
treated, safe temperature 94
varnished, conductivity, heat 303
dielectric strength in oil, test 2105
resistivity, heat 303
Coal, figure of merit, definition 1648
handling machinery, cost 1038
mines. (See Mines).

Coils, field, safe temperature, I. E. C. rules 2163
Commutating pole, advantages, tests 1591
coefficient, leakage flux, definition 1536
useful flux, definition 1536
design difficulties 1589
effect of load 1532
saturation 1531
initial leakage, definition 1533
leakage coefficient 1533
magnetic testing, exploring coil calculation 1528
reluctance, leakage paths 1538
saturation, d-c. machines 1527
Commutators, heating 95
over-load capacity 124
safe heating 95
temperature, I. E. C. rules 2163
Concatenation of induction motors, speed control 1078
Concrete, water-soaked, resistance, electric 1410
Condensers, cost 1863
effect on fuel economy 1986
synchronous, capacity rating 97
compared with line charging current for e.m.f. regulation 891
current calculation 860
distribution systems 1559
example of use 883
operated with series booster 878
operation for constant e.m.f. 1546
rating, ideal 882
saving on transmission lines 884 885
transmission line regulation 1545
with booster, wiring diagram 879
Condenser-type bushing. (See Insulators).
Conduction, electric, metallic, electronic theory 1015
relation to heat 1016
heat, effect of barometric pressure 248
room temperature 242
equation 302
formula 239
relation to electric 1016
Conductivity, heat, gases, temperature coefficient 306
measurement, Nusselt method 384
metallic, calculation 1018
temperature coefficient 305
shape-factor 307
temperature coefficient 305
various materials. (See name of Material).
Conductors, feeder, depreciation 1211
trolley wire, depreciation 1211
Conduits, cable, manhole spacing 407
Constantan, conductivity, heat 303
resistivity, heat 303
Contracts, electric service. (See Rates.)
Control, e.m.f., automatic 859
generators, lighting, motor cars 2026
load, automatic 1694
motor, for rubber mills 1588
power-factor, transmission lines 857
remote, electrical installations 1686
speed, motor, a-c., brush shifting method 1085
induction, commutator motor method 1083
concatenation method 1078 1079
dynamic regulation 1080

Control, speed, motor, a-c., induction (*continued*)
multi-windings..... 1077
regulating motor method, reliability.....1090 1092
regulating set method..... 1081
regulating set method, efficiency..... 1084
rheostatic method..... 1076
rheostatic method, efficiency..... 1084
transmission systems, by synchronous machines..... 855
Convection, effect of air velocity, formula..... 318
barometric pressure..... 247
humidity..... 250
pressure..... 316
room temperature..... 240
temperature..... 316
energy dissipated, different temperatures.....242 243
equation..... 318
film theory..... 314
thickness of film..... 359
forced, effect of air temperature, equation..... 319
temperature coefficient..... 319
theory..... 317
in liquids..... 320
Langmuir law..... 238
Lorenz law..... 312
plane surfaces, temperature coefficient..... 317
Converters, frequency, operation..... 1713
parallel operation, use of synchroscope.... 1717
phase angle variations, formula..... 1728
starting methods..... 1720
with induction motor..... 1720
synchronizing indicators..... 1721
mercury vapor, for railroad work..... 1228
synchronous, 25-cycle, extra losses, correction factor. 495
60-cycle, extra losses, correction factor. 494
artificial loading..... 664
automatic operation..... 1735
capacity rating..... 97
commutating pole, losses, test..... 497
compared with a-c. generators..... 772
extra losses, correction factor..... 490
input-output test, correction..... 489
life.....1632 1682
polarized relay to control polarity in starting..... 1734
scrap value..... 1632
temperature measurement. (See Temperature).
testing corrections..... 489
Conveyors, life..... 1632
scrap value..... 1632
Cooling, convection..... 359
curve, generator..... 181
fog-laden air..... 361
heat flow. (See Heat).
methods, classification..... 236
transformer after load is removed..... 201
air-blast..... 248
conditions..... 214
dissipating power of tanks..... 379
efficiency tests..... 215

Copper, annealed, standard, report I. E. C. Committee 2156
National Laboratories 2164
conductivity, heat 303
conductor, cost 1864
density 2164
expansion, temperature coefficient 2165
heat capacity 352
emissivity 310
industrial, report, National Laboratories 2164
resistance 2164
temperature coefficient 186–228 2164
resistivity, heat 303
specific heat 394
weight 2164
thermal capacity 394
wire. (See Wire).
Corona bibliography 1753
critical intensity, investigation, equipment 1739
ionization theory, failure 1752
variation of conductor size 1744
with density 1749
pressure 1743 1744
temperature 1748
detection with telephone receiver 1818
d-c 1755 1814
effect of hot furnace gases 1759
electrolytic gas production 1763
e.m.f., effect of pressure 1805
relation to air pressure 1806
energy theory 1768
test 1769
zone, criticism 1815
for e.m.f. measurement 1818
formation, effect of pressure 1737 1805
temperature 1737
ionization theory 1751
pressures below atmosphere 1803
fume precipitating apparatus 1757
formula, Peek 1739 1745
Ryan 1738
investigation, apparatus 1739 1756
ionization theory 1751
law, developments 1767
loss, concentric cylinders, Peek's formula 1802
effect of conductor radius, equation 1820
frequency 1819
equation 1820
parallel wires, relation to voltage 1801
relation to impressed voltage 1799
extent of copious ionization 1800
low air densities 1772
tests 1770
metal surfaces, permanency 1818
negative, losses, test 1761
oscillographic study 1787 1812
reference 1823
positive and negative 1755
losses, test 1762
pressures below atmosphere 1803
rubber covered wire 1807
smoke indicator 1764
start on switching 1805

Corona (*continued*)
variation with atmospheric conditions, formula 1746
conductor diameter, formula 1746
pressure 1747
voltage measurement 1811
voltmeter 831
difficulties 1818
Corpuscle, definition 970
Corrosion, electrolytic, definition 1345
effect of circulation of electrolyte 1388
current density 1350 1352
depth in soil 1359 1360
low voltage 1390
moisture 1355 1356
oxygen on end products 1364
temperature 1358
efficiency, causes of variations 1382
definition 1350
formation of galvanic couples 1383
iron, cast, tests 1369
effect of carbonates 1375
chemicals, tests 1371
chlorides 1375
current density 1350
depth in soil 1359
different soils 1377
hydroxids 1375
kind of metal 1367
moisture 1355
nitrates 1375
oxygen 1360
on end products 1364
temperature 1358
in soil, test apparatus 1347
various soils, tests 1345
ingot, tests 1368
wrought, tests 1369
steel, tests 1368
tests, apparatus 1348
Cost, ash handling machinery 1038
block signals 1849
boilers 1038
effect of size 1983
installed 1863
operation 1657
bonding, track 1849
buildings, power plant 1038
cable, iron 1865
steel 1865
cars, railroad, motor 1209
catenary trolley construction 1240
coal handling machinery 1038
condenser equipment 1863
contact rail construction 1859
system, railroad 1849
distribution, electric energy 2004
energy, effect of capacity factor 1669
load factor 1644
size of plant 1981
method of calculation 1619
production 1038
coal mines 1049
exciters 1863

Cost (*continued*)
fuel, coal mine boilers 1037
generators, a-c 1597
insulators, strain 1864 1865
suspension type 1864 1865
lightning arresters 1038
locomotives, electric 1849
freight 1209 1867
operation 1187
passenger 1209 1867
repairs 1166
switching 1209
steam, Mallet type 1242
operation 1187
repairs 1166
motors, synchronous 1597
piping system 1863
pole, tubular steel 1865
wooden 1865
power plant 1038
construction, effect of size 1982
railroad 1849
repairs 1038
steam, construction 1038 1040
operation 1038 1040
public utility, physical property 2084
railroad, 2400-volt, overhead system 1180
distribution system, construction 1209
steam, electrification 1209
repairs, central stations, classification 1620
standardization, desirability 1663
storage batteries 1863
substations, railroad 1209–1849 1858
d-c 1180
transformer 1901
superheater 1038
switchboard 1038 1863
third rail 1859
track bonding 1209
transformers 1863
effect of size 1983
installed 1901
water cooling system 1901
transmission line 1864
construction 1209
steel tower 1251
system, railroad 1849
traveling crane 1863
trolley construction 1209
turbines, steam 1863
wire, copper 1864
trolley 1865
Costs, central station, classification 1620–1659–1664 1680
comparison methods 1649–1661 1676
items, definition 1623
Cotton batting, conductivity, heat 304
resistivity, heat 304
impregnated, safe temperature, I. E. C. rules 2163
non-impregnated, safe temperature, I. E. C. rules 2163
resistivity, heat 340 357
safe temperature 94
tape, varnished, conductivity, heat 303
resistivity, heat 303

Crane travelling, cost 1863
Current, calculation of strength 1017
capacity, cables 325
calculation, accuracy 344
general formula 347
table 387 389
pantograph trolleys 1159
tungsten filament in nitrogen 1937
charging, circuit for elimination from measurements 1792
oscillograph measurement 1787
method 1789
oscillograms, interpretation 1797
corona, wave 1787 1825
definition, ... 1002
density, cables 350
electron theory 1017
high frequency measurement 1287
leakage, oscillograms, interpretation 1807
stray, corrosion. (Also see Corrosion).
density, dangerous 1408
in practice 1408
effect of load-factor 1403
polarization between pipes 1398
reduction with insulated negative returns 1412
significance of loss 1405
soils, different cities 1377
Cyclogram 1825
Damping power, definition 2018
parallel operation 2018
Delays, penalty 1052
Depreciation, determination 1653
functional, definition 1630
physical, definition 1630
power plant, steam 1038
turbo-generators 55
various structures. (See name of Structure).
Diamagnetism distinguished from paramagnetism 1023
Dielectric breakdown, effect of size of electrode 2116
phenomena 2111
solids, probability theorum 2128
field. (See Field electric).
flux in insulator design 934
unit 937
losses, cloth 2119
transformers 450
variation with voltage 451
phenomena, theory 937
rupture, phenomena 2111
strength, cloth, measurement 2119
effect of electrode area, explanation 2124
test 2097
mechanical pressure 2123
various materials. (See name of Material).
Dielectrics in series with air, e.m.f. tests 937
testing, historical review 2117
Distortion ratio, definition 777
derivation 781
Distribution, electric energy, cost 2004
railroad, catenary construction, cost 1240
contact rail, all-day efficiency 1872
cost 1859
itemized cost 1859
maintenance cost 1866

Distribution, railroad, contact rail (*continued*)
system, cost 1849
maintenance cost 1850
rail-size, relation to grade .. 1858
d-c., 2400-volt, cost 1180
trolley, construction cost 1209
system, choice of synchronous and induction motors . 887
e.m.f. limitations 863
railroads, d-c., choice 1160
Diversity-factor, coal mine 1140
load 1107
definition 1988 2001
lighting, commercial 1990
residence 1990
Drexel Inst., evening classes 1424
Earth resistance. (See Soils).
Ebonite, conductivity, heat 303
resistivity, heat 303
Economizers, effect on fuel economy 1986
Eddy-current losses. (See Losses).
Education, competitive system 1451
correspondence course, Penn. R. R 1430
evening classes, division of applicants 1422
Drexel Inst 1424
Franklin Inst 1426
general conditions 1418
Philadelphia Textile School 1428
possibilities 1421
problems 1418
Spring Garden Inst 1428
Temple Univ 1427
Univ. of Washington 1446
Y. M. C. A., Philadelphia 1426
Nat'l. Ass'n. of Cor'pn. Schools 1413
dues 1415
membership 1414
purpose 1414
professional, sorting material 1451
School of Telegraphy, Penn. R. R 1431
vocational, apprenticeship 1433
schools, Penn. R. R 1437
schools, Penn. R. R., outline of work 1439
Bell Telephone Co., Philadelphia 1432
city employees, Philadelphia 1434
danger 1445
definition 1444
Drexel Inst 1417 1424
Philadelphia and vicinity 1417
Trade School 1429
reading technical magazines 1449
scope 1423
training of instructor 1448
Efficiency, all-day, converter substation 1872
locomotives, electric 1872
railroad distribution system 1872
electric 1872
transmission line 1872
calorimetric method 645
converters, synchronous 490
25-cycle 495
60-cycle 494
inverted 491

Efficiency (*continued*)
cooling, transformers 215
engines, gas 798
steam, compound condensing 797
fractional load, operating temperature, standardization recommendations 608
generators, a-c 488
bucking series motor car lighting 2057
d-c., by different methods 485
commutating pole 485 486
slipping clutch motor car lighting 2057
input-output method, commercial accuracy 536
criticism 638
d-c. motors 486
synchronous converters 490
25-cycle 495
60-cycle 494
inverted 491
locomotives, steam, Mallet type 1165
Pacific-type 1152
machines, electric, sources of error 551
motor-generator sets 498
motors, a-c. commutator 1086
induction, calculation 430
recommendation for standardization 434
squirrel cage 1125
d-c., commutating pole 483–485 486
by different methods 485
phase characteristic method, advantages 640
railroads, electric mountain-grade 1180
separation losses method, a-c. generators 488
d-c. generators 486
motors 485
motor-generator sets 498
synchronous converters 490
synchronous converters, 25-cycle 495
synchronous converters, 60-cycle 494
synchronous converters, inverted 491
short-circuit losses method, advantages 633
turbines, steam 799
water 798 800
effect of head 800 802
volt-ampere, standardization 604
Eider down, conductivity, heat 304
resistivity, heat 304
Electric field. (See Field).
Electricity, explanation 1000
positive, definition 1007 1012
Electrolysis (Also see corrosion, electrolytic.)
corona current 1763
high-tension 1763
E.m.f., measurement, corona, tests 1741
high-frequency 1287
high-tension, method 740 818
independent of frequency 1813
ratio of maximum to mean 1741
sphere gap 812 827
first suggested 830
Electrons, definition 970

Electrons (*continued*)
explanation Zeeman effect 1008
kinetic energy, relation to temperature 1018
motion equation 1007
Thomson theory 957
universal existence 1010
Electron-theory 999
of electricity 1002
matter 1005
Electroscope, gold leaf 954
Elements, chemical, building up 989
Elevators, life 1632
scrap value 1632
Emanation, definition 977
density 978
liquifying temperature 978
Energy, 0.1 cent per kw-hr 1989
production, cost 1038
effect of size of plant 1981
units, conversion factors 412
Engineer, definition 1272
manual, definition 1272
theoretical, definition 1272
Engineering organization, proposed 1273
skeleton constitution 1274
societies, Amer. Soc'y of Civil Engrs., position 1279
co-operation 1275
Engine-room, costs, classification 1624 1627
Engines, Corliss, condensing, cost of energy output 1679
gas, 4-cylinder, turn-over torque 2050
6-cylinder, turn-over torque 2050
efficiency 798
rating in myriawatts 414
steam, compound condensing, efficiency 797
life 1632 1682
rating in myriawatts 414
scrap value 1632
Exciters, cost 1863
life 1632
scrap value 1632
Fans, ventilating, mine, power requirements 1073
Fibre, horn, heat conductivity 156
Field, electric, about bushings 902
dielectric sphere 909
dielectrics of various shapes 898
ring and rod 900
suspension insulators 905
equations 910
exploration apparatus 896
in presence of solid dielectrics 894
intensity equations 910
plotting experimentally 895
magnetic, work to establish 1002
Figure of merit, definition 1648
Fire-risk, automatic, substations 1696
generators, a-c. turbo 33
Flickering, incandescent lamps, causes 1954
Flux, dielectric, in design of insulators 934
unit definition 937
leakage, coefficient, definition 1536
useful, coefficient, definition 1536
Force, magnetic, at any point, equation 1002
Franklin Inst., evening classes 1426

Frequency changers. (See Converters, frequency).
measurement 774
telephone circuits 1286
Friction coefficient, determination 559
effect of speed 561
formula 572
variation with speed 574
various types of brushes at different speeds 563
losses, formula 574
measurement 571
Fuel, cost, coal mine boilers 1037
economy, effect of condensers 1986
economizers 1986
superheaters 1986
figure of merit, definition 1648
Fullerboard, heat conductivity 156
varnished, conductivity, heat 303
resistivity, heat 303
Fume indicator, corona type 1764
Furnaces, life 1632
scrap value 1632
Galvanometer, moving coil, Weston, sensibility 1811
Generators, a-c., artificial loading 650
Behrend method 716
methods 667
capacity rating 96
commutating pole, saturation 1527
cost 1597
eddy currents, effect of load 504
e.m.f. wave shapes 749
extra loss, correction 488
induction, limitations of capacity 796
performance characteristics 796
remote control 1687
life 1632 1682
loading for temperature tests, methods 650
losses. (See Losses).
phase characteristics, tests 513
rating, kilovolt-amperes 151
regulation. (Also see Regulation).
determination by test 783
saturation curve, calculation 847–851 852
construction 791
test 514
scrap value 1632
synchronous, effect of load change 2016
impedance, test 514
temperature measurement. (See Temperature).
rise, correction factor 275
tests 677
testing, alternate open circuit and short circuit method 654
d-c. open-delta method 658 672
temperature distribution 674
methods 711
open-circuit and short-circuit method 669
open-circuit and short-circuit method advantages 650
open-circuit and short-circuit method compared with actual load 652
open-circuit and short-circuit method disadvantages 650

Generators, a-c., testing (*continued*)
open-circuit and short-circuit method merits 718–719 720
open-circuit and short-circuit method temperature distribution 671
phase displacement method 675
separation losses method, standardization rules 506
zero power factor method 662 668
temperature distribution 669
turbo, axial type 16
critical speeds. (See Speeds).
depreciation 55
design 1
difficulties, earlier types 1
limitations 10 46
fire-risk 33
heating, calculations 58
hottest points 71
in stator 69
insulation 25
losses 31
milled-in-slot type 4
output, maximum, determination 47
equation 48
parallel slot compared with radial slot 7
limitations 9
rotor 5
pheripheral speeds, actual 8
pole flux, equation 48
radial slot type 3
limitations 9
regulation. (Also see Regulation) 34
effect of slot form 45
rotor construction 35
insulation 29
without through-shaft, introduction 2
short-circuit characteristics 34
temperature problem 19
ventilation 10 65
voltage selection 64
wave shapes, effect of load 756
pole shape 751
typical 761
constant-speed motor, car lighting, advantages 2037
cooling curve 181
critical speeds. (See Speeds).
d-c. artificial loading 664
care of brushes and commutators 612
commutating pole, design difficulties 1589
distribution 1537
leakage calculation 1542
coefficient 1533
paths 1538
reluctance paths, calculation 1538
saturation 1527
stray loss correction factor 485
testing, separation losses method, accuracy 485–486 487
lighting, motor cars 2026
clutch type 2037
losses 2073
slipping clutch, test 2053

Generators (*continued*)
rating, choice 795
Rosenburg, for motor car lighting 2074
short-circuit tests 372
stator coils, heating 153
temperature measurement. (See Temperature.)
rise, correction factors 274
effect of room temperature 259
test 372
testing, overvoltage run 401
voltage selection 64
German silver, conductivity, heat 303
resistivity, heat 303
Glass, quartz, conductivity, heat 303
resistivity, heat 303
Glycerine, conductivity, heat 304
resistivity, heat 304
Going value, definition 2089
Gold enamel, heat emissivity 310
Graphite, conductivity, heat 303
resistivity, heat 303
Gravel, resistance, electric, tests 1399 1400
Gutta-percha, characteristics 1883
conductivity, heat 303
for splicing joints 1885
insulation resistance, effect of rosin 1884
resistivity, heat 303
Hall effect, explanation 1022
Heat capacity, various materials. (See name of Material).
conduction, concentric cylinders, formula 308
parallelopipedons 308
spheres, formula 308
equation 302
formula 239
generators, turbo 22
planes, formula 308
shape factor 307
conductivity, gases 304
insulating materials 156 303
liquids 304
metals 303
minerals 303
various materials. (See name of Material).
convection, Lorenz law 312
dissipation, bibliography 313
calculation 321
capacity, transformer tanks 245
convection 359
effect of humidity 249
pressure 247
temperature of cooling medium 239
flow in electric machines 371
general theory 236
surface resistivities 322
total 321
transformer tanks 379
ventilated surface 67
emissivity, various materials. (See name of Material).
flow, armature coil 83
in electrical machinery 83
generators, turbo 20
laminated structure 61 67
turbo-generator 61

Heat (*continued*)
radiation. (See Radiation).
resistivity, gases 304
insulating materials 303
liquids 304
metals 303
minerals 303
various materials. (See name of Material).
transmission, electrical machinery, laws 301
Heating, house, electricity 1990
loaded cables 333
calculations 335
tests 337
rates, cables, calculation 351
Hoisting, mine, power requirements 1123
Hoists, life 1632
scrap value 1632
Horn fibre, heat conductivity 156
Humidity, air, calculation 256
correction for vapor pressure 255
measurements 255
Hunting, synchronous machines 2014 2018
Hydrogen, atom mass 963
effect on tungsten lamp performance 1922
Hysteresis losses. (See Losses.)
effect of wave distortion 837
Ice loading, transmission lines, test 1835
on transmission lines, test 1833
Ignition, energy of spark 2068
motor cars 2043
timer and distributor construction, motor car 2067
Impedance, iterative, definition 1336
measurement 471
Indeterminate losses. (See Losses, extra).
Institute activities, limitations 1261
annual report 2167
Board of Directors, publicity 1266
local Sections, purpose 1264
offices, competition, advisability 1267
requirements 1268
publications, limitations 1262
Instruments, commercial measurements, accuracy 533
electrical, commercial accuracy 535–640 641
life 1632
location to avoid errors 553
scrape value 1632
transformers. (See Transformers).
Insulating cloth, testing apparatus 2119
materials, aging, relation to temperature 2125
dielectric strength, determination, test 2097
testing apparatus 2098
testing, standardization recommendations 2122
Insulation, breakdown, effect of size of electrode 2116
phenomena 2111
cellulose, safe temperature 26
circuits in mines 1060
cotton, safe temperature 94
design 893 907
effects of frequency 947
fibrous 80
life 106
safe temperature 25–75 106
temperature, effect on life 81

Insulation (*continued*)
fire-proof 80
generators, turbo 25
rotor 29
heat-resisting 80
effect on life 82
safe temperature 94
high-frequency 936
losses, transformers 450
materials, classification 80
mica, Hafely process 28
of pipes from stray currents 1411
paper, safe temperature 94
safe temperatures 79
solid, breakdown, phenomena 2113
probability theorum 2128
tape, safe temperature 25
temperature, standardization recommendations 89
testing, historical review 2117
thermal capacity 394
transformers, design 914
weak point theory, objections 2127
Insulators, bushing, condenser type, limitations 944
effect of frequency 947
surface conduction 948
line, oil, tests 1491
pin-type, design 923
insulation 1476
specifications for testing 1465
rain tests 1503
specifications 1468–1475 1483
specifications 1471
electrical testing 1473
testing 1471
strain, high-tension, trouble 1492
suspension, arc-over test, specification 1458
cost 1864
design 924
electric field 905
hardware, cost 1864
inspection 1477
performance under electrical and mechanical stress, tests 1488
specifications 1457 1462
for testing 1457 1462
voltage gradients 1828
Washington Wtr. Pwr. Co., standard construction 1831
oil, tests 1499
puncture strength, specifications 1470
strain, cost 1864
suspension, hardware, cost 1864
wall bushing, design 927 940
Integraph, principle 1340
use 1340
I. E. C. Berlin, meeting, organization 2152
report 2151
Ion, charge, measurement 960
definition 970
Ionium, kinetic energy of alpha particle 985
velocity of alpha particle 985
Ionization instant of copious, definition 1794
of gases, theory 957
voltage at copious 1794

Iron, cast, conductivity, heat 303
heat emissivity 310
resistivity, heat 303
surfaced, electrolytic corrosion, tests 1369
unsurfaced, electrolytic corrosion, tests 1369
conductivity, heat 303
corrosion 1387
electrolytic, investigation 1345
ingot, electrolytic corrosion, tests 1368
resistivity, heat 303
saturation, Kapp method 1527
steel, heat capacity 352
wrought, electrolytic corrosion, tests 1369
Iron-loss transformers. (See Transformers).
Isolated plants vs. central station for coal mines 1046
Kapp method of obtaining iron saturation 1527
Kelvin, definition 937
vortex-atom hypothesis 999
Krarup loading system, telephone cables 1883
advantages 1889
Labor reduction factor 1657
for comparison of cost 1641
Lamps, carbon, metalized, compared with tungsten, nitrogen-filled 1950
specific consumption 1913
choice for motor cars 2023
incandescent, blackening, theory 1953
flickering, effect of filament diameter 1954
gas filled, experiments, early 1949
maximum theoretical efficiency 1913
relative efficiency, various types 1950
Nernst, instability 2010
Novak, reason for failure 1949
tantalum, compared with tungsten, nitrogen-filled 1950
tungsten, blackening, causes 1913
control of deposit 1931
methods of prevention 1927
compared with lamps, tungsten, nitrogen-filled 1950
effect of argon 1924
carbon dioxide 1923
monoxide 1923
hydrogen 1922
methame 1924
nitrogen 1922
oxygen 1922
various gases 1921
water vapor 1923
evaporation of filament 1914
failure, cause, investigation 1926
gas from bulb 1920
filament 1919
lead-in wires 1920
in bulb, sources 1918
high efficiency, description 1935
theory 1913
large size, life, limitations 1915
manufacture, washing, definition 1916
nitrogen-filled 1929
bulb design 1938
compared with other lamps 1950
description 1935
filament current capacity 1937
design 1936
intrinsic brilliancy 1943

Lamps, tungsten, nitrogen-filled (*continued*)
lead-in wires and supports..... 1939
light distribution..... 1944
photometry, method..... 1944
photo-micrographic work..... 1947
specific consumption..... 1935
tests.....1930 1941
various types..... 1940
residual gas..... 1918
specific consumption.....1913
use of high pressure gases..... 1927
water vapor elimination, methods..... 1925
Langmuir convection law..... 238
Latent heat, various materials. (See name of Material).
Lead, heat capacity..... 352
resistivity, heat.....340 357
Leakage coefficient, initial, definition..... 1533
gap, definition..... 1534
magnetic, calculation..... 1542
Life, physical property. (See Proper Names).
power plant equipment..... 1632
Lighting, commercial, diversity factor..... 1990
motor cars..... 2023
automatic, desirable features..... 2052
bucking series generator, objections..... 2071
performance..... 2062
test..... 2056
constant-speed generator, advantages..... 2037
charging characteristics..... 2038
disadvantages..... 2074
generators, losses..... 2073
ideal system..... 2025
shunt generator, electric control..... 2029
slipping clutch generator, performance..... 2062
test..... 2056
variable speed generator, charging characteristics..... 2038
vibratory field control generator, tests..... 2055
wiring..... 2034
residence, diversity factor..... 1990
train, automatic, desirable features..... 2052
remote control, equipment..... 1686
Lightning arresters, cost..... 1038
electrolytic, housing construction..... 1895
installation, mountain substation..... 1894
over-voltage limitations..... 864
Load characteristics, coal mines, tests..... 1104
curve, central station, winter..... 803
Chicago down-town..... 1700
coal mines, tests..... 1106
mine plant..... 1122
mountain railroad..... 1862
Load-factor, coal mines.....1049–1108 1140
definition.....1112–1113–1114–1116–1117–1118–1653 1672
determination, method..... 1043
effect on Corliss engine..... 1679
cost of energy production..... 1644
formula..... 1678
electrolysis..... 1403
steam turbine..... 1679
stray currents..... 1403
improvements, mines, coal..... 1128

Load-factor (*continued*)
mines, coal 1128
breaker 1128
cutter 1128
haulage 1128
hoist 1128
lighting 1128
pumping 1128
repair shop 1128
ventilation 1128
Loads, diversity-factor. (See Diversity-Factor).
peak, Chicago down-town 1700
measurement 1117–1118–1131 1134
Loam, resistance, electric, tests 1400
Locomotives, electric, 108-ton, weight on drivers 1154
all-day efficiency 1872
coal consumption, compared with steam 1156
mine operation 1141
compared with Mallet type 1166
steam 1193
cost 1849
of operation compared with steam 1171
depreciation 1212 1219
drawbar pull, calculation 1175
energy consumption 1179
cost 1187
engine house expenses 1223
freight, cost 1209 1867
spare time 1206
time distribution 1230
free running 1206
in engine house 1206
on road 1206
trailing weight 1202
fuel cost 1171
hauling capacity on grades, compared with steam 1231
lubricants, cost 1187
mine operation, requirements 1066
N. Y. Central, time distribution 1208
passenger, cost 1209 1867
express service 1153
spare time 1206
time distribution 1230
free running 1206
in engine house 1206
shops 1206
on road 1206
Penn. R. R., repair, cost 1218
repairs and maintenance cost 1166
compared with steam 1217
cost 1171–1178–1212 1850
speed-torque characteristics 1193
stores, cost 1187
switching, compared with steam 1183
cost 1209
wages, cost 1171–1178–1187 1213
freight, time distribution 1230
hauling capacity on grades, electric vs. steam 1231
N. Y. Central, repair, cost 1217
passenger, time distribution 1230
steam, Atlantic type, mileage 1216
repairs, cost 1216

Locomotives, steam, Atlantic type (*continued*)
weight distribution..... 1216
coal consumption, compared with electric.... 1156
for firing up..... 1254
compared with electric..... 1193
consolidated simple type, mileage..... 1216
repairs, cost..... 1216
weight distribution. 1216
type, speed-torque characteristics..... 1193
cost of operation compared with electric.... 1171
depreciation.....1212 1219
drawbar pull, calculation..... 1175
engine-house expense.....1187 1223
freight, mileage..... 1216
repairs, cost..... 1216
spare time..... 1205
time distribution..... 1230
free running..... 1205
in engine house..... 1205
shops..... 1205
on road..... 1205
trailing weight..... 1202
weight distribution..... 1216
fuel cost.....1171 1187
hauling capacity on grades, compared with electric..... 1231
lubricants, cost..... 1187
Mallet type, coal consumption.....1164 1182
compared with electric locomotive..... 1164
cost..... 1242
of operation.....1183 1185
efficiency..... 1165
fuel, cost..... 1186
mileage..... 1184
repairs, cost..... 1186
wages, cost..... 1186
mechanical efficiency..... 1253
Pacific-type, efficiency..... 1152
mileage..... 1216
performance..... 1151
repairs, cost..... 1216
tractive effort..... 1151
weight..... 1151
distribution..... 1216
passenger, mileage..... 1216
repairs, cost..... 1216
spare time..... 1205
time distribution..... 1230
free running..... 1205
in engine house..... 1205
shops..... 1205
on roads..... 1205
weight distribution..... 1216
repairs and maintenance cost..... 1166
compared with electric..... 1217
cost.....1171–1187–1212 1850
stores, cost..... 1187
switching, compared with electric..... 1183
mileage..... 1216
repairs, cost..... 1216
weight distribution..... 1216
wages, cost.....1171–1187 1213

Lorenz law, heat convection 312
Losses, brush contact 559
drop, various current densities 562
temperatures 563
types 562
resistance, formulas 583
measurement 565
tests 578
method 579
variation with brush pressure 568
current density 570
humidity 570
lubrication 570
materials 568
speed 568
surface conditions 567
temperature 569
factors that effect 577
friction 559
converters, synchronous, commutating pole, variation with load, test 497
inverted, variation with load, test 492 493
variation with load, test 492 493
copper, transformer, effect of temperature rise 600
core, definition 592
exponent 591
generators, a-c., different methods of testing 507
variation with load 512
voltage 511
motor, induction 591
eddy-current, generators, a-c., effect of load 504
extra 590 591
converters, synchronous, 25-cycle, correction factor 495
25-cycle, correction factor recommended for standardization 501
60-cycle, correction factor 494
60-cycle, correction factor recommended for standardization 501
correction factor 490
correction factor 483
feasibility 632
determination, commercial accuracy 536
from input-output test 531
input-output method, commercial accuracy 536
effect of interpole flux 622
generators, a-c., correction factor 488
recommended for standardization 501
method of determining 503
notes 519
recommendations for standardization 626
d-c 523
correction factor recommended for standardization 501
variation with load 526
various types 526 529
machines, electric, correction factor 627
motor-generator sets, correction factor 498

Losses, extra (*continued*)
motors, d-c 523
correction factor 485
recommended for standardization 501
induction 429
classification 435
copper under load 424
core tests 425
under load 424
effect of slots 425 426
load 423
small size 433
tests 436
synchronous, correction factor recommended for standardization 501
rotating machines, determination 479
terminology 587
transformer 439 465
copper, equation 474
core-type, tests 440
correction 598
magnetic-shunt-type, test 443
shell-type, tests 441
friction, formula 574
generators, a-c., circulating energy method 510
test 510
phase characteristic method 509
method, advantages 640
method, test 510
separation losses method, tests 507–508 510
short-circuit method, merits 631
turbo 31
variation with load 515
tests 487
hysteresis 594
input-output method, criticism 638
merits 631
iron, definition 592
machines, electric, circulating energy method 623
measurement, calorimetric method 645
motors, d-c., commutating pole, variation with load, test. 482
stray. (See Losses, extra).
transformer, copper, analysis 465
effect of temperature rise 600
mathematical theory 466
core-type, test 440
dielectric 450
load 439
magnetic-shunt-type, tests 443
no-load 439
effect of frequency 454
temperature, test 453
voltage 458–459–460 461
low-tension coils only, effect of voltage 462
one terminal grounded, effect of voltage 463
terminals free, effect of voltage 463
variations with voltage 452
recommendations for standardization 464
shell-type, test 441
Machinery, electric, cooling. (See Cooling).
losses. (See Losses).
" pumping back " test method 481

Machines, commutating, care of brushes and commutators..... 612
electric, copper loss temperature, determination..... 396
correction factor for extra losses..... 483
d-c., efficiency tests..... 523
errors in testing, sources..... 551
high-voltage, temperature gradients..... 130
iron loss temperature, determination..... 396
loading back test connection..... 481
name plate stamping..... 98
operating temperature, definition..... 606
rating method..... 91
regulation, operating temperature, standardization recommendation..... 608
safe temperature..... 94
specifications, meaning..... 117
starting with oil pressure in bearings..... 1736
synchronous, effect of load change..... 2016
for transmission line control... 855
hunting..... 2014
temperature, maximum.....121 122
measurement. (Also see Temperature).
rise, correction factors..... 274
ultimate..... 93
testing, various. (See name of Machine).
tests, commercial..... 712
rotating, temperature by thermometers, method..... 172
Magnetic field. (See Field).
Magnetism, electron hypothesis..... 1023
Marble, conductivity, heat..... 303
resistivity, heat..... 303
Mass, dependence upon velocity of electron..... 999
Matter, electron theory..... 1005
Measurements, electrical, commercial accuracy.....535–640 641
instruments, commercial accuracy 533
of temperature. (See Temperature).
various quantities. (See name of quantity).
Mercury, boiling point..... 2133
various pressures..... 2134
gas, specific heat..... 2135
latent heat of vaporization..... 2134
liquid, specific heat..... 2134
specific heat..... 2134
switches. (See Switches).
vapor, boiler construction..... 2144
setting..... 2146
energy available at different pressures..... 2137
for turbine operation..... 2133
turbine system, design..... 2138
Meters, location..... 1042
Methame, effect on tungsten lamp performance..... 1924
Mica, composition..... 39
conductivity, heat..... 304
resistivity, heat..... 304
compounds, safe temperature..... 109
conductivity, heat.....156–303 405
change with pressure..... 405
paper, conductivity, heat..... 303
resistivity, heat..... 303
resistivity, heat..... 303
safe temperature.....24–75 94
I. E. C. rules..... 2163
Micanite, heat conductivity..... 156
safe temperature, I. E. C. rules..... 2163

Milliammeters, soft iron vane type, inductance 833
Millivoltmeters, commercial accuracy 534
Milner, oscillographic study of corona 1812 1823
Mines, accidents caused by electricity, prevention 1059
reduction by electricity 1061
statistics 1070
coal, boilers, loss 1036
breaker, load-factor 1128
power-factor 1128
requirements 1127
central station supply 1035
advantages 1035
cutting, load-factor 1128
power requirements 1126
power-factor 1128
diversity-factor 1140
electric energy production, cost 1111
service, central station, early installations 1098
history 1097
disturbances 1099
requirements 1029 1097
energy production, cost 1049
haulage, load-factor 1128
power-factor 1128
hoisting, load-factor 1128
power-factor 1128
lighting, load-factor 1128
load-factor 1049–1108–1128 1140
improvements 1128
locomotives, electric, operation 1141
operating day 1030
power requirements 1121
tests 1103
power-factor 1128
improvement 1128
pumping, load-factor 1128
power-factor 1128
repair shop, load-factor 1128
ventilation, load-factor 1128
power-factor 1128
voltage 1047
electric service, central station supply 1097
trouble factors 1058
shocks, sources 1055
explosions caused by electricity 1056
fires caused by electricity 1056
hoisting. (See Hoisting).
locomotive, electric, requirements 1066
power requirements 1121 1902
pumping, power requirements 1126
safeguarding use of electricity 1055
ventilation, power requirements 1073–1087 1124
Monel metal, heat emissivity 310
Motor cars, ignition 2043
energy of spark 2068
interrupter, varying angular contact time with speed 2047
system for constant potential 2044
timer and distributor construction 2067
lighting system. (See Lighting).
starting motors, performance 2064
timer and distributor construction 2067
Motor-generator sets, extra losses, correction factor 498

Motors, a-c., adjustable speed for fans 1075
commutator, brush shifting, efficiency 1086
power-factor 1086
reliability 1090 1092
constant-speed for fans 1074
induction, artificial loading 677 685
methods 683
efficiency 1125
calculation 430
instability 2008
losses. (See Losses).
power-factor 1125
speed control methods. (Also see Control).
speed-torque characteristics 2008
stability of operation 2008
temperature distribution 679–688 689
rise, correction factor 275
equation 725
tests 677
tests, feeding-back method 677
methods 683 711
reduced voltage method 678
reversed rotation method 680
merits 724
zero power-factor, merits 722
synchronous, advantages 1595
compared with induction 1606
motors, reasons 1608
cost 1597
for power-factor regulation 1597
distributing end, advantages 1598
easy starting air compressor 1564
pump 1563
effect of excitation on armature current when voltage is applied 1524
effect of load change 2016
for transmission line regulation 1547
industrial use 1559
non-synchronous running 1522
oscillations due to load change 2017
oscillograms, interpretation 1607
pull-in torque, explanation 1611
relation between armature and field currents 1520
round type vs. salient type 1612 1614
running partial load, field, short circuit. 1522
self-starting, disadvantages 1589
solid pole, starting performance, tests. 1616
starting characteristics 1509
current characteristic 1511 1512
field circuit, closed 1510
open 1510
methods 1510
partial voltage 1515 1516
stages 1510
tests 1518
torque 1513 1514
usefulness 1605
temperature measurement. (See Temperature).
characteristics for rubber mills 1586
d-c., care of brushes and commutators 612
commutating pole, advantages, test 1591

Motors, d-c., commutating pole (*continued*)
care of brushes and commmutators 612
design difficulties 1589
extra loss correction factor 485
flux distribution 1537
leakage calculation 1542
coefficient 1533
paths 1538
reluctance, leakage paths, calculation 1538
separation losses method, accuracy 485–486 487
enclosed, temperature distribution 260 269
rise, correction factors 274
life 1632
mine fan, selection 1074
motor-car starting, performance 2064
open, temperature distribution 267
rise, correction factors 274
scrap value 1632
semi-enclosed temperature distribution 268
rise, correction factors 274
speed control. (See Control).
temperature distribution 260
measurement. (See Temperature).
rise, correction factors 274
effect of room temperature 259
Myriawatt, argument for introduction 411
in terms of other units 412
rating of various prime movers 414
Name plate stamping 98
standardization recommendation 100
National Association of Corporation Schools. (See Education).
Needle-gap, calibration, effect of humidity 813
inconsistency 733
Nitrogen, effect on tungsten lamp performance 1922
Oil, dielectric strength, effect of electrode area, test 2106
test 2106
electric breakdown, phenomena 2113
mineral seal, viscosity, effect of temperature 244
paraffin, conductivity, heat 304
resistivity, heat 304
viscosity, effect of temperature 244
transil, viscosity, effect of temperature 244
viscosity; effect of temperature 244
Oscillograms, Braun tube 1823
charging current to corona conductor 1793
Oscillograph for measuring charging current 1787
sensibility 1811
Oxygen, depolarizing effect 1387
effect on corrosion of iron 1360
end products of corrosion 1364
tungsten lamp performance 1922
Paper, asbestos, conductivity, heat 303
resistivity, heat 303
fish, heat conductivity 156
rope, conductivity, heat 303
resistivity, heat 303
varnished, conductivity, heat 303
resistivity, heat 303
safe temperature 94 326
varnished, heat conductivity 156
Para rubber, conductivity, heat 303
resistivity, heat 303

Paraffin, conductivity, heat 303
resistivity, heat 303
Parallel operation, a-c. machines 1714
damping power 2018
frequency converters 1713
effect of armature inductance 1725
synchronizing power 2018
synchronous converters, use of synchroscope 1717
Paramagnetism distinguished from diamagnetism 1023
Peak load. (See Load).
Peek formula, corona 1739 1745
loss, concentric cylinders 1802
Peltier effect, explanation 1021
Penn. R. R., apprenticeship schools 1437
correspondence course 1430
school of telegraphy 1431
Petroleum, conductivity, heat 304
resistivity, heat 304
Philadelphia Textile School, evening classes 1428
Trade School, vocational instructions 1429
Piping, life 1632
power plant, cost 1863
scrap value 1632
Planck's law 1011
Polarization between buried pipes 1398
Pole-lines, construction, labor, cost 1866
steel, construction, cost 1865
wood, construction, cost 1865
Poles, depreciation 1211
tubular, steel, cost 1865
wood, cost 1865
Porcelain, absorption of moisture 1487 1503
conductivity, heat 303
insulation resistance, effect of firing 1496
insulator, effect of lightning frequencies 1497
manufacture 1495
specifications 1462–1465–1472 1480
vitrification temperature, importance 1495
resistivity, heat 303
safe temperature 94
Potential transformers. (See Transformers, Shunt).
Power measurement, three-phase, two wattmeters, accuracy 642
requirements, coal cutting 1126
mines 1029–1035 1121
tests 1103
hoisting, mine 1123
mines 1121
coal breaker 1127
fans 1073 1087
pumping 1126
ventilation 1124
pumps, coal mine 1036
rubber calendering 1585
machinery 1583
masticating 1584
mills 1586
mixing 1584
refining 1584
tubing 1585
warming 1585
washing 1583
Power-factor, cloth, measurement 2119

Power-factor (*continued*)
control, transmission lines 857
correction, effect of rates 1044
effect on electric energy rates 1134
improvements, mines, coal 1128
measurement 1136
mines, coal 1128
breaker 1128
cutting 1128
haulage 1128
hoist 1128
pumping 1128
ventilaton 1128
motors, a-c. induction, squirrel cage 1125
Power-plants, amortization, calculation 1633
buildings, cost 1038
capacity-factor, definition 1669
effect on cost 1669
construction, cost 1038
effect of size 1982
cost, classification 1659–1664 1680
comparison, method 1649–1661 1676
effect of load-factor 1644
formula 1678
itemized 1863
standardization, desirability 1663
economies due to increase in size 1985
economy, effect of condensers 1986
economizers 1986
superheaters 1986
isolated. (See Isolated plants).
advantages 1991 1999
labor, cost 1863
load-factor, effect on costs 1644
operation, cost 1657 1863
railroad, cost 1849
operation cost 1850
rating of units, choice 795
repairs, cost 1038
size, effect on cost of operation 1981
steam, construction cost 1040
fixed charges 1040
labor, cost 1863
operation cost 1038 1040
repairs 1038
President's address 1261
Presspahn conductivity, heat 156 303
resistivity, heat 303
Prime movers rated in myriawatts 414
rating, choice 795
Probability, theorum 2128
Promotor, proposition 2082
Promotion costs 2087
Propagation constant, definition 1337
Protection, automatic, substations 1695
Public service rates. (See Rates).
utility accounts, classification 2093
capital expenses 2086
cost, physical property 2084
going value 2089
organization, expenses 2086
promotion, cost 2087
problem 2082

Public utility (*continued*)
reasonable charge, definition 2078
service, cost, elements 2093
sinking fund 2091
Pumping, mines, power requirements 1126
Pumps, coal mine, power requirements 1036
life 1632
scrap value 1632
special, for synchronous motor drive 1564
Pupin coil-loaded system, advantages 1888
Pyro-electrolytes, definition 2009
volt-ampere characteristic 2011
Pyrometers, resistance. (See Thermometers).
Radiation, bibliography 313
black body 1010
from radioactivity substances 963
heat, effect of barometric pressure 247
humidity 249
room temperature 239
energy dissipated, different temperatures 241
equation 296
Stephan-Boltzman's law 237, 309
temperature coefficient, formula 311
Wein's law 311
Radioactive equilibrium, definition 995
Radioactivity 953
determining age of world 987
discovery 954
disintegration theory 971
heating effect 984
Radium A, kinetic energy of alpha particle 985
velocity of alpha particle 985
atomic weight 956
C, kinetic energy of alpha particle 985
velocity of alpha particle 985
content, common rocks 987
discovery 956
disintegration products 979
stages 979
emanation, density 978
kinetic energy of alpha particle 985
liquifying temperature 978
velocity of alpha particle 985
F, kinetic energy of alpha particle 985
velocity of alpha particle 985
heating effect 984
kinetic energy of alpha particle 985
period, determination 982
velocity of alpha particle 985
Railroads, capacity limit 1174
electric, all-day efficiency 1872
Butte, Anaconda & Pacific Ry 1162
coal consumption, compared with steam 1156
construction cost 1180
contact roller, current capacity, effect of speed 1159
cost of operation, calculation 1178
d-c., 2400-volt system 1159
5000-volt 1229
mercury rectifier 1228
vs. single-phase 1227
depreciation 1211
distribution system. (See Distribution).
fuel, cost 1869

Railroads, electric (*continued*)
main line service 1155
mountain-grade efficiency 1180
performance 1161
operation cost 1188–1210 1850
vs. steam 1157
from central station 1246
purchase of energy, advantages 1225
rates for energy 1249
single-phase vs. d-c 1227
substations. (See Substations).
trolley, cost of operation 1195
engine-house expenses, electric locomotives 1223
steam locomotives 1223
equipment, depreciation 1211
freight traffic, trailing weight, electric locomotive 1202
steam locomotive 1202
fuel consumption, calculation 1871
cost 1869
locomotives required for given service, steam 1205
maintenance of structures, cost, effect of electrification 1211
way, cost, effect of electrification 1211
mountain, cost of operation 1169
electric operation compared with steam 1167
electrification, cost 1849
problem 1173 1237
study 1845
operation cost, electric vs. steam 1210
steam vs. electric 1210
ruling grade, definition 1192
signals. (See Signals).
steam, coal consumption, compared with electric 1156
cost of operation 1195
calculation 1181
electrification 1189
cost estimate 1209
d-c., 2400 volts 1149
effect on operating expenses 1191
mountain-grade, problem 1173 1237
problem 1149 1196
reasons for 1189
results, experience 1190
study 1197
fuel consumption, calculation 1871
cost 1869
mountain grade, electrification, advisability 1237
operating expenses, effect of locomotives 1192
road characteristics 1191
ruling grade 1192
operation cost 1188–1210 1850
vs. electric 1157
passenger express service, requirements 1151
steam performance 1151
service, coal consumption 1153
traffic analysis 1198
classification 1195
freight, time distribution, locomotives, electric 1206
locomotives, steam 1206
locomotive, mileage required, electric 1204
steam 1204
number, determination 1239

Railroads, traffic (*continued*)
passenger, time distribution, locomotives, electric 1206
locomotives, steam. 1206
switching, time distribution, locomotives, electric 1207
locomotives, steam. 1207
transportation expenses 1213
Rates, analysis 1041
coal mines 1041–1129 1141
ideal 1139
contract, coal mines, suggestions 1141
for mines, suggestions 1136
penalty for delays 1052
determination 1143 1144
effect of meter location 1042
power-factor 1134
correction 1044
flat with fixed charge 1130
for electric railroads 1249
ideal 1137
maximum demand, determination 1042
system 1130
off-peak 1138
for coal mines 1030
public service, elements determining 2093
utility, factors that determine 2077
Rating at point of highest efficiency 119
capacity, electric machinery 92
generators, a-c 96
synchronous condensers 97
converters 97
transformers 97
continuous, electric machinery 93
electric machinery, methods 91
functions 139
maximum capacity, objections 102
report of I. E. C. Committee 2153
service, classification 95
electric machinery 92
from central station viewpoint 114
short time, electric machinery 93
Rays, alpha, counting particles 966
description 965
mass of particles 966
particles, counting method 994
definition 970
Becquerel, discovery 954
beta, description 963
particle, definition 970
penetrating power 964
cathode, characteristics 990
particle, definition 970
gamma 967
definition 970
Röntengen, discovery 954
Reduction factor for labor 1641
use 1657
Regulation, distribution system with synchronous motors 1559
electric machines, operating temperature, standardization recommendation 608
e.m.f., automatic with synchronous condensers 1561
load limitations 863
generators, a-c., calculation, advantages 846
method 847

Regulation, generators, a-c. (*continued*)
determination 789
Adams' method 851
by test 783
errors 846
Kapp's method 852
method 846
standard rule, criticism 784
standardization recommendation 786
effect of pole leakage 786
Institute method, errors 784
Potier's triangle method 789
turbo 34
effect of slot form 45
transformer, equation 474
formula derivation 602
transmission line, calculation 856
constant e.m.f. 1545
cost 1549
receiver e.m.f. 871
effect of charging current 891
power factor 865
synchronous condensers 1545
motor advantages 1547
Relays, automatic telephone 1307
polarized, automatic telephone 1307
Repairs, cost, central stations, classification 1620
Report, annual 2167
Board of Examiners 2185
Code Committee 2175
Constitutional Revision Committee 2183
Edison Medal 2184
Editing Committee 2174
Educational Committee 2171
Electric Lighting Committee 2172
Electrochemical Committee 2173
Electrophysics Committee 2173
Finance Committee 2186
High-Tension Transmission Committee 2172
Indexing Transactions Committee 2174
Industrial Power Committee 2172
Institute membership 2185
John Fritz Medal 2184
Law Committee 2175
Library Committee 2175
Meetings and Papers Committee 2170
N. Y. Reception Committee 2171
Organization Intern'l Elec'l Congress Committee 2184
Patent Committee 2182
Power Station Committee 2173
Public Policy Committee 2181
Railway Committee 2171
Relations of Consulting Engineers Committee 2183
Sections Committee 2169
Standards Committee 2174
Telegraphy and Telephony Committee 2173
U. S. Nat'l Committee of I. E. C. 2183
Use of Electricity in Mines Committee 2174
Resistance, earth. (See Soils).
insulation, cloth measurement 2119
measurement, hot 198

Resistance, measurement (*continued*)
loaded coils 203
neutralization of inductive effect 199
potentiometer method 198
temperature determination 178
voltmeter-ammeter method 198
various bodies. (See name of Body).
materials. (See name of Material).
Respiration, artificial, Schafer prone-pressure method 1063
Resuscitation, Schafer prone-pressure method 1063
Röntgen rays, discovery 954
Room temperature. (See Temperature).
Rosenburg generator, bibliography references 2074
for motor car lighting 2074
Rotors, generators, a-c., safe temperature 153
temperature distribution, observed 170
safe temperature, I. E. C. rules 2163
turbo-generator, design 46
insulation 29
limitations 46
parallel slot 5
compared with radial slot 7
limitations 9
radial slot 3
advantages 38
compared with parallel slot 7
limitations 9
through-shaft 2
Rubber calendering, power requirements 1585
conductivity, heat 302 303
deterioration by high voltage 44
ozone 44
heat capacity 352
industry, electrical requirements 1583
insulation, dielectric strength, test 2099
machinery, power requirements 1583
masticating, power requirements 1584
mills, power requirements 1586
mixing, power requirements 1584
refining, power requirements 1584
resistivity, heat 303–340 357
safe temperature 326
sheet, dielectric strength, variation with electrode area, test 2101
in oil, dielectric strength, effect of electrode area, test 2108
test 2108
tubing, power requirements 1585
warming, power requirements 1585
washing, power requirements 1583
Ryan formula, corona 1738
Sand, resistance, electric, tests 1399 1400
Schafer prone-pressure method of artificial respiration 1063
School of Industrial Arts, Trenton 1435
Schools, National Association of Corporation Schools 1413
Scrap value, definition 1632
Segregated losses method. (See Losses).
Series transformers. (See Transformers, series).
Shellac, conductivity, heat 303
resistivity, heat 303
Shunts for d-c. instruments, commercial accuracy 534
Shunt transformers. (See Transformers, shunt).
Signals, block, cost 1849
Silver, conductivity, heat 302
heat emissivity 310

Sinking fund, importance 2091
Slate, conductivity, heat 303
resistivity, heat 303
Smoke indicator, corona type 1764
Soils, Albuquerque, N. M., resistance, tests 1400
Apollo, Pa., resistance, tests 1400
effect on electrolytic corrosion 1377
Erie, Pa., corrosion efficiency, test 1380
resistance, test 1400
Philadelphia, resistance, tests 1399
Pittsburgh, Pa., corrosion efficiency, tests 1380
resistance, tests 1400
resistance, different sources 1398
effect of mechanical pressure, tests 1397
moisture 1393
temperature, tests 1394
investigation 1390
St. Louis, resistance, tests 1399
Washington, D. C., resistance, tests 1400
Southern Pacific R. R., Tehachapi Pass, electrification study 1845
profile 1847
tunnel clearances 1875
Spark-gaps, spheres, advantages over needle-gap 736
brass, gradient curve 1778–1779 1780
spark-over curve 1778–1779 1780
calibration 739
curve 744–747 813
effect of grounding 813
various pressures 1750
construction 735 1773
corrections, various altitudes 820
effect of radius on gradient 1781
spark-over 1781
electron theory 1784
e.m.f. calibration 739
measurement, first suggested 830
factors affecting accuracy 822
gradient calculation 1782
effect of diameter 2113
manufacture, difficulty 820
merits for measurement 733
performance 1774
potential gradient, effect of radius 817
range of usefulness 827
spark-over voltages 815
standardization recommendations 736
steel, gradient curve 1777
spark-over curve 1777
voltage measurement 812
Specific consumption, carbon lamps 1913
tungsten lamps 1913
nitrogen-filled 1935
heat, various materials. (See name of Material).
Specifications, electric machinery, meaning 117
various apparatus. (See name of Apparatus).
Speed control. (See Control).
critical, advantage in running below 63
running above 74
Sphere spark gap. (See Spark Gap.)
Spring Garden Inst., evening classes 1428
Standardization rules, American compared with European 112
correction factors for extra losses, recommendations 501

Standardization rules (*continued*)
efficiency, fractional load, temperature recommendations 608
Institute compared with I. E. C. 107
I. E. C. compared with Institute 107
recommendation for brush friction determination 564
recommendations for definition of transformer losses 464
recommendations for induction motor efficiency 434
Standards Committee, history 110
Stators, generators, a-c., safe temperature, estimation 154
temperature rise calculation 158
temperature rise calculation 158
Steel braided armor, resistivity, heat 340 357
conductivity, heat 303
machine, electrolytic corrosion, tests 1368
resistivity, heat 303
transformer, conductivity, heat 303
resistivity, heat 303
Stephan-Boltzman's radiation law 237 309
Stokers, effect on cost of operation 1657
life 1632
scrap value 1632
Storage battery. (See Batteries).
Stray currents. (See Currents).
losses. (See Losses, extra).
vs. load losses, terminology 587–589–597 621
Substations, automatic, connection diagram 1691
equipment 1691
fire risk 1696
operation 1693
description 1685
protection 1695
basement type, layout 1701
building, portable 1892
design, cost limitations 1973
fire hazard 1973
operating requirements 1972
safety 1973
space economy 1971
Detroit, map 1689
electric railways, spacing 1160
industrial 1955
electrical design 1957
physical design 1957
motor-generator, cold storage plant 1969
vehicle charging 1969
mountain, construction 1891
portable 1891
railroad, automatic 1910
cost 1209-1849 1858
depreciation 1211
d-c., cost of construction 1180
heating loads 1852
labor, cost 1858
maintenance, cost 1211
mercury converter 1228
operation cost 1850 1858
portable 1905
repairs, cost 1858
spacing, calculation 1852
different grades, chart 1855

Substations (*continued*)
sub-basement type, layout 1702
sub-grade, classification 1701
synchronous converter, all-day efficiency 1872
automatic, equipment 1691
operation 1693
basement and sub-basement, design 1699
car manufacturing plant 1963
pumping plant 1970
ship and engine building plant 1961
type manufacturing plant 1966
underground, layout 1710
transformer, amusement park 1963
cost 1901
grain elevator 1960 1967
layout 1896 1958
operation, cost 1901
paper mill 1964
remote control 1686
rubber mill 1966
silk manufacturing plant 1958
upkeep, cost 1901
underground, construction 1705
layout 1710
piping 1708
type 1699
ventilation 1704
Superheaters, cost 1038
effect on fuel economy 1986
Switchboard, cost 1038 1863
life 1632
scrap value 1632
Switches, circuit breakers, rating 807 809
method 731
standardization recommendation. 811
rupturing capacity 732
mercury, battery disconnecting for motor car lighting .. 2065
Switching, effect of voltage control 862
Symbols, electrical, table 2161
mathematical 2162
report of E. I. C. Committee 2159
units 2162
Synchroscope indications, interpretation with frequency converters. 1717
Synchronizing indicators for frequency converter starting 1723
power, definition 2018
parallel operation 2018
Telephone lines, artificial, connection diagram 1284
experimental investigation 1283
current equations 1339
measurement 1287
vector diagram 1291–1293 1295
e.m.f. equations 1339
vector diagram 1291–1293 1295
frequency 1286
Krarup loading system 1883
measurement, bibliography 1303
potential measurement 1287
Telephones, automatic, calling circuit, polarized ringing 1326
office circuit 1322
guarding against grounded ringing 1328
long distance, circuit connections 1310 1314
method of operation 1308
operation 1305

Telephones, automatic (*continued*)
Northwestern Long Distance Telephone Co. 1305
office line circuit 1330
toll line apparatus, connection 1323
repeater apparatus, connection 1327
trunking circuit, operation 1318
frequency 1286
iterative impedance, definition 1336
propagation constant, definition 1337
submarine, cable, electrical properties 1879
laying 1877
protective apparatus 1882
Temperature distribution, armature coil 84
generators, a-c. 669–671–673–674–675 676
rotor, observed 170
motors, a-c. induction 678–679–680–681–688 689
enclosed 260 269
open 267
ventilated 267
semi-enclosed 268
rating machines, tests, equipment 262
transformers 446
parts 224
water-cooled 247
effect on insulation 79
electric machinery 93
generators, a-c., determination 177
stator coils 153
turbo, rotor 30
gradients, high-voltage machines 130
insulating materials, standardization recommendations 89
local, measurement, electric machines 185
maximum, bearings 135
cables 326
commercial machines 75
fibrous insulation 106
generators, a-c. turbo, calculation 71
stator 69
mica compounds 109
various substances. (See name of Substance).
measurement, generator cooling curve 181
hot spots in machines 370–373–375 376
machines, electric 163 185
methods 86
oil bath 193
resistance change 164 178
compared with thermometer and exploring coils 180
exploring coils 165–179 201
compared with thermometer and resistance change 180
disadvantages 368
experience 362
limitations 370

Temperature measurement, resistance exploring coils (*continued*)
location .373 374
precautions . 188
method 86
error 187
rotating machines 163 185
standardization recommendation 174
thermocouples 166 188
accuracy 168
advantages 363
disadvantages .363–368 397
limitations 370
thermometers 87 164
application 171
compared with resistance and exploring coils 180
mercury 191
resistance, advantages 364 397
disadvantages .187 364
transformer cooling medium 193
correction for lag 195
idle unit method 208
method 191 215
room correction 195
standardization recommendation 211
with idle unit 204
motors, a-c., determination 177
operating, for electrical machines, definition 606
rise, cables 391 392
calculation by resistance 228
stator 158
commutators 95
conductor, bare 328
lead covered 327
converters, synchronous loading 664
copper conductors, corrected formula 228
correction factor, generators, a-c 275
motors, enclosed 274
induction 275
open 274
semi-enclosed 274
rotating machines 274
effect of air pressure 286 292
temperature 284 295
atmospheric conditions 279 289
tests 281 289
humidity 293
electric machines, effect of atmospheric conditions 235
tests, factory 649
methods 650
generators, a-c., alternate open-circuit and short-circuit tests 654
artificial loading 650
d-c. open-delta tests 658
loading methods 667
separate open-circuit and short-circuit tests 650
turbo, calculations 58
zero power-factor, tests 662

Temperature rise, generators (*continued*)
d-c., loading 664
effect of room temperature 259
turbo 19
maximum, electric machines 121 122
measurement, electric machines, corrections 381
room temperature correction 378
motors, effect of room temperature 259
induction, loading methods 677 685
resistance formula, correction for copper and iron losses and room temperature 231
room correction 229
method, calculation 210
tests, factory methods 649
transformers, calculation 398
correction, standardization recommendation 257
effect of atmospheric conditions 235 279
humidity 255
pressure 253
surrounding air 252
idler transformer correction 726
loading methods 693
water-cooled 247
correction factors 184
definition 171
determination 177
measurement, artificial lagging of thermometer 366
safe, insulating materials. (See name of Material)
limits, I. E. C., rules 2163
transformers, conditions affecting 213
correction for room temperature 227
tests, open and short-circuit method 223
Temple Univ., evening classes 1427
Testing, electrical machinery. (See Machines, electric).
various machines. (See name of Machines).
Thermal capacity, various materials. (See name of Material).
resistivity. (See Heat).
Thermocouples. (See Temperature measurement).
Thermodynamic, efficiency 2133
Thermoelectric phenomena 1020
Thermometers, artificial lagging 366
mercury, accuracy 192
method of application 171 177
resistance, accuracy 192
construction 291
disadvantages 187
spirit, accuracy 192
Thermostat, use in transformers 1898
Third rail, bonding, cost 1859
construction, cost 1859
maintenance, cost 1866
Thomson effect, explanation 1021
Thorium, disintegration products 983
stages 983
Tools, life 1632
scrap value 1632
Towers, Washington Wtr. Pwr. Co., standard construction 1830
Track bonding, cost 1209–1849–1859 1860
depreciation 1211

Track (*continued*)
maintenance cost 1850
with electric locomotives 1850
steam locomotives 1850
ruling grade, definition 1192
Transformers, air-blast, cooling 248
temperature correction 251
alarm protection 1900
artificial loading 218–691 725
capacity rating 97
commercial tests 704
cooling. (also See Cooling).
curves 202
efficiency tests 215
medium, temperature measurement 193
copper loss tests 706
core-type, insulation design 914
performance test 440
cost, effect of size 1983
current. (See Transformers, series).
dielectric losses at various voltages 451
efficiency, volt-ampere, standardization 604
exciting voltage, importance 864
heat run, method of loading 217
tests 691 707
high-tension, insulation design 914
impedance measurement 471
tests 706
installed, cost 1901
instrument, commercial accuracy 534
insulation losses 450
tests 708
iron-loss tests 705
life 1632
load inductance, equation 469 601
resistance, equation 469 601
losses (See Losses)
tests 439
magnetic shunt type, tests 443
magnetizing current, tests 705
oil-cooled, temperature distribution 224
over-potential tests 708
performance one terminal grounded, no-load 458
performance, effect of frequency 454
temperature 453, 454, 455 456
equation under short-circuit 469
tests, circuit diagram 472
polarity tests 704
polyphase, core-type, insulation design 917
vs. single-phase 1908
potential (see Transformers, shunt)
ratio, definition 727
tests 704
regulation, equation (also see Regulation) 474
formula derivation 602
resistance measurement with load on 203
tests 705
Scott-connected, tests, loading-back method 692
scrap value 1632
self-cooled, heat test 446
temperature distribution 446
series, commercial accuracy 554
shell-type, insulation design 919

Transformers, shell-type (*continued*)
performance test 441
shunt, commercial accuracy 554
single-phase vs. polyphase 1908
step-up, cost 1863
tanks, energy dissipation, different types 245
temperature, correction for room temperature 227
distribution, tests 224
measurement (see Temperature)
methods 215
rise, calculation 398
corrections, standardization
recommendations 257
effect of atmospheric conditions
235 279
humidity 255
pressure 253
surrounding air 252
terminals, design 920
testing, artificial loading 217
commercial 704
copper loss 706
heat run 204, 691 707
idle unit method 208
impedance 706
insulation 708
intermittent loading method 693
iron loss 705
loading methods 691 725
compared 696 697
loading-back method 691
magnetizing current 705
open and short-circuit method 219
over-potential 708
polarity 704
ratio 704
resistance 705
standardization recommendation 211
thermostat, protection 1898
three-phase, artificial loading 218
with idle unit 204
water-cooled heat dissipation capacity 246
test 447
temperature distribution 225, 247 447
water relay 1897
Transmission line, all-day efficiency 1872
bill of materials 1864
catenary construction 1565
charging current, magnitude 889, 890
conductor spacing 892
constant e.m.f., current capacity 1548
performance characteristics 1548
saving affected 1548
construction, cost 1864
labor, cost 1865
depreciation 1211
design for constant drop 866
e. m. f. control, automatic 859
by synchronous machines 855
experimental, for ice test 1834
generator e. m. f. to maintain constant receiver e. m. f. 870, 871

Transmission line (*continued*)
ice loading, effects 1829
operation 855
saving with synchronous condensers 884, 885
with synchronous condensers 875
pole (see Pole line)
regulation (also see Regulation)
calculation 856
effect of power-factor 865
for constant receiver e.m.f. 871, 1545
limitation of various loads 863
without synchronous condensers 874
sag, effect of ice loading 1835
steel tower, cost 1209, 1251
suspension insulator, deflection, effect of ice loading 1839
voltage drop, effect of power-factor 857
system, 100-mile, cost with constant e.m.f. regulation 1556
ordinary e.m.f. regulation 1556
performance, constant e.m.f. regulation 1556
ordinary e.m.f. regulation 1556
200-mile, cost with constant e.m.f. regulation 1556
ordinary e.m.f. regulation 1556
performance, constant e.m.f. regulation 1556
ordinary e.m.f. regulation 1556
constant e. m. f. 1545
advantages 1555
disadvantages 1555
-drop formula 1555
maintenance, cost 1866
railroad, cost 1849
use of synchronous and induction motors for power-factor control 888
Traps, life 1632
scrap value 1632
Trolleys, catenary construction, cost 1240
pantograph, current capacity, effect of speed 1159
wire, depreciation (also see Wire) 1211
Tungsten lamps (See Lamps)
Turbine, mercury vapor 2133
steam, cost 1863
of energy output 1679
efficiency 799
life 1632
rating in myriawatts 414
scrap value 1632
water, efficiency, effect of head 800, 802
output, maximum 799
rating in myriawatts 414
specific speed, definition 798
Units, energy, conversion factors 412
myriawatt, definition 411
symbols 2162
Univ. of Washington evening classes 1446
Uranium, energy released 997
kinetic energy of alpha particle 985
velocity of alpha particle 985
X, decay and recovery law 972
definition 972

Valves, life 1632
scrap value 1632
Ventilation, air cleaning 18, 53, 1732
axial 65
investigation 66
circumferential method, disadvantages 41
generators, turbo 11
air passages, design 52
air-gap method, difficulties 13
axial 65
blower 17
circumferential method 13
disadvantage 41
mine, adjustable speed fan 1075
power requirements 1073, 1087, 1124
underground substation 1704
Voltmeters, commercial accuracy 534
corona (also See Corona voltmeter) 831
difficulties 1818
electrostatic, for high tension e.m.f. 740
sphere gaps (see Spark gaps, spheres)
Vortex-atom hypothesis 999
Wages, assistant switchboard operator 1864
boiler cleaner 1863
repairer 1863
chief engineer 1863
operator 1864
clerk 1863
dynamo cleaners 1864
tenders 1864
firemen 1863
load dispatchers 1864
machinist 1863
helper 1863
meter testers 1864
oilers 1863
switchboard operators 1864
turbine operators 1863
watch engineers 1863
water tenders 1863
wipers 1863
Water, conductivity, heat 304
resistivity, heat 304
vapor, effect on tungsten lamp performance 1923
Wattmeters, commercial accuracy 533
Waves, electric, iterative impedance, definition 1336
propagation constant, definition 1337
over conductors, bibliography 1303
Wave-shape distortion, 10 per cent rule, criticism 766, 775
analysis 768
control 835
effect of capacity 767
inductance 767
resistance 767
on electrical apparatus 765
hysteresis loss 837
generators, a-c. compared with synchronous converters 772
limitations 842
measurement 832, 845
apparatus 779
ratio, definition 777
derivation 781

Wave-shape distortion (*continued*)
sources 839, 840
specification 778
standardization 834
recommendations 780
sifting out harmonics, method 1791
standardization, recommendations 775
various apparatus (See name of Apparatus)
Windings, short-circuit, safe temperature, I. E. C. rules 2163
Wire, copper, cost 1864
enamelled, safe temperature, I. E C. rules 2163
rubber-covered, corona 1807
trolley, cost 1865
Wiring diagram, converter substation 1962, 1970
substations, automatic 1691
transformer substation 1959, 1965
motor cars 2034
double-wire vs. single-wire 2058
problem 2071
single-wire, objections 2070
Wood, white pine, conductivity, heat 304
resistivity, heat 304
Woolen wadding, conductivity, heat 304
resistivity, heat 304
Y. M. C. A., Philadelphia, evening classes 1426
Zeeman effect 1008

A paper presented at the 279th Meeting of the American Institute of Electrical Engineers, New York, January 10, 1913.

Copyright, 1913, By A. I. E. E.

HIGH-SPEED TURBO-ALTERNATORS—DESIGNS AND LIMITATIONS

BY B. G. LAMME

The real problems in the design of turbo-alternators did not really develop until the high-speed, large capacity units came into demand. In the earlier work, the difficulties in design were mostly those due to lack of experience and to insufficient knowledge of the possibilities of materials, etc. As more data were obtained, the speeds and capacities were gradually increased, until with the present large capacities and high speeds a number of conditions are encountered which may be considered as true physical limitations.

The principal difficulties in the design of the earlier machines were found in the permissible weight which could be carried by bearings, undue noise due to the open construction of the machines, and the troubles incident to the through-shaft construction of the rotor.

The bearing problem was eliminated by securing more complete data, which showed that the possibilities in this feature had hardly been touched upon.

The solution of the noise problem was largely one of enclosing the machine without interfering with the ventilation. In doing this, the noise problem was practically eliminated, but the greater problem of ventilation then developed.

In overcoming the difficulties of the through-shaft construction, the first great advance was made in the direction of larger outputs at higher speeds. In very high-speed machines, the diameter of the shaft in the rotor core is necessarily small. As the over-all diameter of the core is comparatively small, it follows that, after allowing for the slot depth, and the metal in the

core necessary to withstand the high rotative stresses, there is left but little available space for the shaft. About 600 kv-a. capacity at 3600 rev. per min. was the limit with this construction.

The first great advance in this problem was made by the introduction of rotors without the through-shaft. By this means, the parts of the shaft adjacent to the rotor core proper could be very much heavier than with the through-shaft type, and this, combined with the solid rotor core, gave great stiffness or rigidity compared with the former through-shaft type. This allowed much larger cores, with correspondingly increased outputs. The two-pole parallel slot type of rotor with bolted-on shaft construction, as described later, was apparently a leader in this respect, due to mechanical, rather than electrical, characteristics. When this type had proved to be a successful one, the possible capacities of two-pole, 3600-revolution, 60-cycle machines at once jumped from 600 to 1000 kv-a., and this was

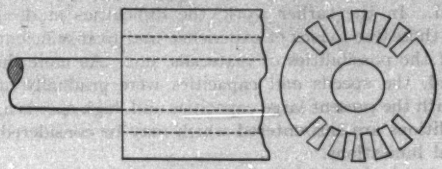


FIG. 1

quickly followed by 1500, 2000 and 3000-kv-a. units at 3600 revolutions. Since then, the increase in capacity at this speed has been more gradual, but has been carried up to 5000 kv-a. at present, with possibilities of a 6250-kv-a. unit.

The radial slot type of rotor, also described later, when constructed with its core and shaft in one piece, quickly followed the parallel-slot type in the above growth, and may eventually catch up with its only rival in the two-pole, 60-cycle field of construction.

About the same time that the through-shaft type was superseded in the two-pole, 60-cycle machine, a corresponding change was made in the two-pole, 25-cycle, and in four-pole rotors for both frequencies, so that, at the present time, practically no designs for the highest-speed machines use the through-shaft type of construction. This latter, however, has been retained in some of the more moderate speed large-capacity units.

On account of the high rotative and peripheral speeds, the general design of large capacity turbo-generators turns upon the type and construction of the rotor, rather than the stator. Various designs and types of rotors have been developed, but, with rare exceptions, only two general types are now built in this country. These may be designated as the radial-slot and the parallel-slot types. Each has a number of advantages over its rival and each has given good results in practise.

Radial Slot Type of Rotor

In the radial slot type, as usually constructed for high-speed machines, the core and shaft are forged in one piece in the smaller and more moderate sizes, but may be built up of a number of separate plates or disks bolted rigidly together in the larger sizes. In this type, the core is cylindrical in all cases, and in the outside surfaces are radial slots, usually arranged in groups, in which the

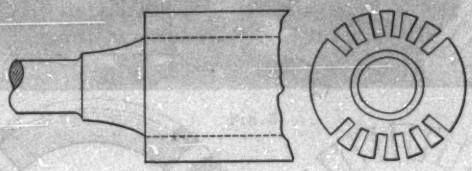


Fig. 2

exciting windings are placed. While all radial slot types of rotors bear a general resemblance to each other, yet there are marked differences in the method of forming the slots and teeth which constitute the outer surface. In some types the solid rotor core has radial slots milled or slotted in the main body of the core. In other cases the slots are formed outside the main core by inserted teeth, usually with overhanging tips, between which the exciting coils lie. These two general constructions are illustrated in Fig. 3. Examples of the inserted-tooth construction are found in the large moderate-speed rotors of one American company, and in somewhat higher speed machines of a German company. However, with the advent of the high-speed, high capacity machines, the milled-in construction of the radial slots appears to be taking the lead, due to certain mechanical limitations in the inserted-tooth types.

On account of the radial slots and the usual concentric arrange-

ment of the exciting coils, the field or exciting turns cannot be assembled and insulated before placing on the core, except in the inserted-tooth type of construction. With the milled-in slot type, the field conductors, usually of flat strap, are dropped into the slot one at a time, with insulation between individual turns. For ease of winding, the ends are usually allowed to overhang the core, and require a very ample outside support in the very high-speed machines. This is illustrated in Fig. 4. The completed coils are usually held in place by strong non-magnetic wedges in the tops of the slots. These wedges are usually carried by overhanging pole tips, in the inserted-tooth type, or by grooves in the sides of the slots in the milled-slot type. The design of the supports for the overhanging end windings has furnished one of the difficult problems in this type of construction. Examples

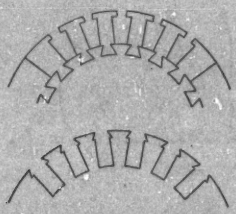


Fig. 3

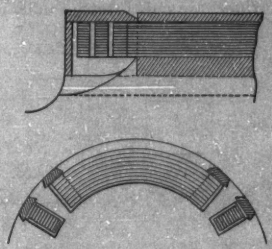
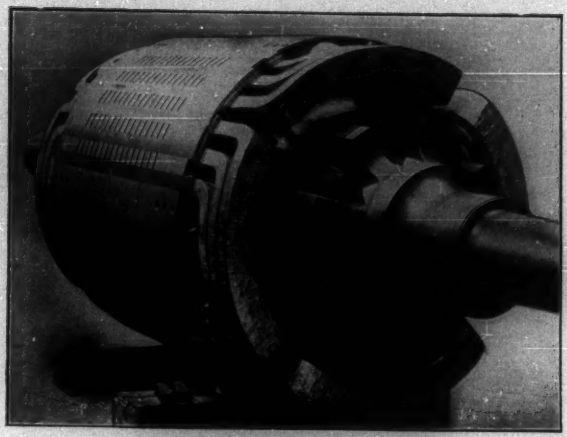


Fig. 4

of radial-slot end windings, and of the rotor complete, are shown in Figs. 5 and 6.

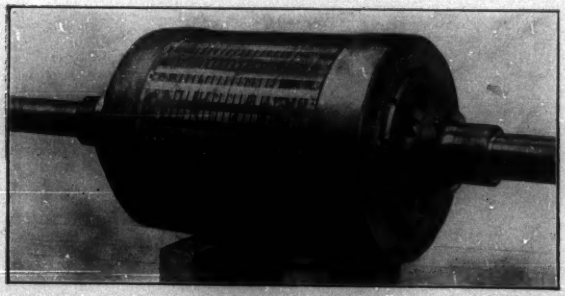
This general construction of the radial slot type of rotor is obviously applicable to machines of any number of poles. With a two-pole machine there will be only two groups of coil slots and two groups of concentric coils, while with four poles or six poles there will be four or six groups respectively. It is evident that, with this construction, a cylindrical rotor is obtained, regardless of the number of poles. It is also evident that the problem of supporting the end windings becomes an increasingly difficult one, as the number of poles is decreased and the span of the end windings is correspondingly increased.

The support over the end windings usually consists of a heavy ring which, in very high-speed machines, must consist of material



[LAMME]

FIG. 5



[LAMME]

FIG. 6

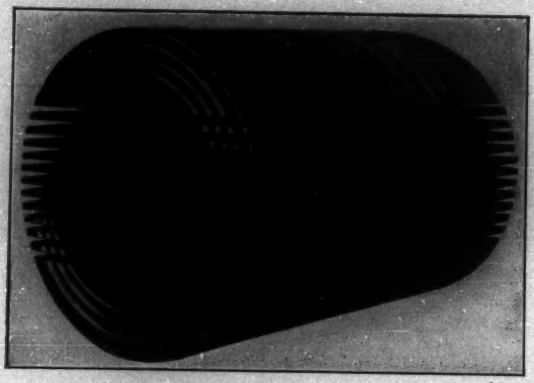


FIG. 7 [LAMME]

FIG. 8 [LAMME]

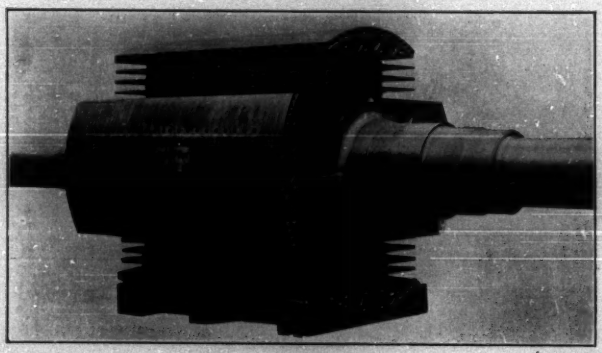


FIG. 9 [LAMME]

having extra good physical characteristics, for this ring must not only be able to carry itself, but must also carry the weight of the underlying end windings which it supports. In the German inserted-tooth rotor, the end windings are supported by steel bands of many layers, instead of the solid steel ring. In some of the lower speed radial slot machines, such as one American type with inserted teeth, the end supports are of ring form, usually made in a number of sections, which are bolted to an inner shelf by numerous bolts extending from the outer ring between the coils of the end windings to the inner shelf. While this construction is satisfactory for the more moderate peripheral speeds, yet with the much higher speeds in some of the later practise, this construction has been superseded by a solid ring type of support.

Parallel-Slot Type of Rotor

In the parallel-slot type of rotor, the slots for the exciting coils, for any number of field poles, lie in planes parallel to one another and to the rotor axis. The arrangement is illustrated by Fig. 7. As usually constructed, the slots are cut across the ends of the poles, as well as in the sides, so that the exciting coils are embedded in metal throughout their length. The object of this general arrangement of parallel slots is to facilitate the winding of the exciting coils. The rotor can be placed upon a turn-table, or similar device, and rotated, to wind the coils in place under tension. Two or more coils can be wound at the same time, as is actually done in practise. As the coils can be wound under tension, and as the conductors usually consist of thin flat strap, which can be wound in very tightly, the resultant winding is a very substantial piece of work. The finished winding is supported by metal wedges over the coils.

It is obvious that, with this construction, no external support is required for the end windings, as the field core proper furnishes the necessary support. It was largely on account of this feature of well supported end windings that the parallel-slot type took a leading position during the growth of the larger two-pole, 60-cycle alternators. With the radial-slot type, the support of the end windings presented a more difficult problem in the large capacity, high-speed, two-pole machines, which, however, is being gradually solved.

In the two-pole, parallel-slot construction, in order to utilize the available winding space to advantage, it is necessary for the windings to cover the central portion of the core end where the

shaft is usually attached, as shown before in Figs. 7 and 8. Therefore, with this construction, a separate "head" or driving flange must be bolted to the core at each end, this head carrying the shaft, as shown in Fig. 8. To avoid magnetic shunting of the field flux, this driving head must be made of non-magnetic material, usually of some high grade bronze, to which the shaft is attached in such a way as to keep the magnetic leakage as low as possible. This makes a good strong construction, but is necessarily rather expensive, due to the bronze driving heads. As these cost but little more for a long rotor than for a short one, the construction therefore tends toward relatively long, small-diameter cores in order to lessen the relative dimensions of the bronze heads.

In two-pole, *single-phase* machines of this construction, the copper cage damper for suppressing the armature pulsating reaction on the field is comprised partly of these bronze heads, which form the "end rings" for the copper bars embedded in the slots in the rotor face.

In the four-pole, parallel-slot machine, no bolted-on driving heads are necessary, for the core proper and the shaft may be cast, or forged, in one piece, or in two or more pieces, which are bolted or "linked" together to form a solid core. The principal difference between the two-pole and the four-pole parallel slot constructions, is that the latter must have salient or projecting poles, in order to utilize the parallel construction for the slots, while the two-pole machine is preferably made cylindrical. Fig. 9 illustrates this feature.

It is evident that there is considerable available space lost by the openings between the projecting poles, while the sections of the poles themselves are cut down very materially by the slots for the exciting winding. The limitations, therefore, in such a rotor are in the magnetic section of the field poles and in the available copper space, and in these features the four-pole parallel slot rotor is inferior to the radial slot type. In the two-pole machine, however, the difference between the radial slot and the parallel slot is not nearly so pronounced, as is indicated in Fig. 10 where the two arrangements are shown on one core for comparison. It may be seen from this that, in the two-pole form, the two constructions approach each other, to a certain extent, some of the slots in the parallel construction being radial, while others depart but little from the radial. One disadvantage in the two-pole, parallel-slot type, however, lies in the smaller amount of

copper space which is obtained, for the slot space must necessarily cover a less proportion of the total circumference than is permissible with the radial slot type. This winding space is limited by the physical requirements as regards bending and breaking strains in the overhanging tip *a* in Fig. 10. In the radial slot type, the slot space has no such limitation. Also, on account of the grouping of the field copper into a narrower zone in the parallel slot type, the heat conduction from the copper presents a more difficult problem than in the radial type.

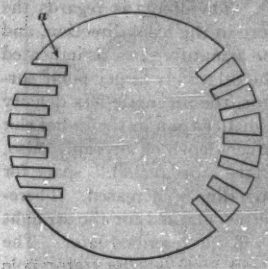


FIG. 10

At first glance, it would appear that the effective length of the field core in the parallel slot type is very considerably diminished by the slots across the ends of the core. However, this is only an apparent effect, for the true length of the core should be taken as that inside of the winding slots, and it should be considered that the additional

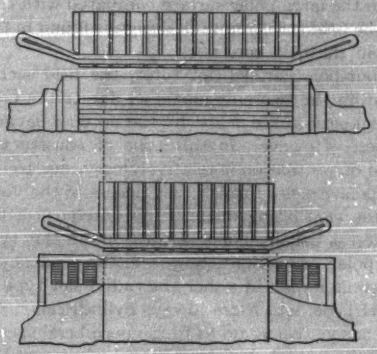


FIG. 11

length of the core at the pole face is in the nature of a coil support which takes the place of the separate support in the radial slot type. Therefore, if over-all lengths, including rotor coil supports, are compared in the two types, there is but little difference, as indicated by Fig. 11. However,

if the armature core is made of the same width as the pole face, in both types of rotors, then in the parallel-slot type it will be materially greater than in the radial, for the overhanging pole tips of the parallel-slot machine are also effective magnetically in furnishing flux to the armature. Therefore, as regards the stator, this tends toward a wider core in the axial direction, and a shallower depth of iron back of the armature slots, as indicated in Fig. 12. Also, on account of the relatively larger polar surface, in the parallel slot type of rotor, the magnetic flux density in the air gap is usually relatively smaller than in the radial slot type, which conduces towards a larger depth of air gap. Also, on account of the larger polar surface, the available space for armature slots and teeth is correspondingly increased. Therefore, this type of construction is better adapted for the straight air gap method of ventilation, as will be described later. The greater section available for slots and teeth at the stator pole face permits a large number of ventilating ducts. The relatively large depth of gap allows a large amount of air to be fed through the air gap to the ducts. Therefore, the "radial" type of stator core ventilation has been used very largely with this type of rotor construction. In the parallel-slot type of rotor, it is obvious that, due to the large polar surface compared with the minimum section of the field core, a limit in design is found in the magnetic saturation in the field core itself.

In the four-pole parallel-slot rotor, the field section is more limited than in the two-pole machine, due to the fact that considerable magnetic space is lost by the notches between the projecting poles. However, in this type of construction, the air gap method of ventilation is relatively easy, due to the fact that these interpolar spaces furnish easy access of the ventilating air to the stator ventilating ducts. In consequence, the problem of ventilation is usually not a serious one in this type of rotor. Due to the polar projections, however, the tendency to noise is obviously greater than in either the radial-slot type or the two-pole parallel type, which are always cylindrical.

Nothing has yet been said as to the peripheral speeds obtained in some of the actual designs of the higher speed generators. These, in themselves, indicate some of the limitations which now confront the designer.

In the 5000-kv-a., two-pole, 3600-rev. per min., 60-cycle generator already referred to, which is of the parallel-slot rotor construction, the rotor diameter is 26 in. (66 cm.). This gives a

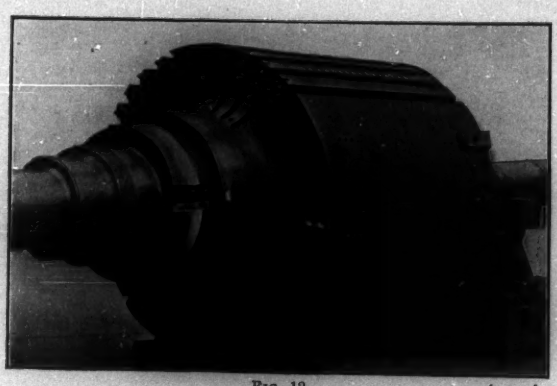


FIG. 12 [LAMME]

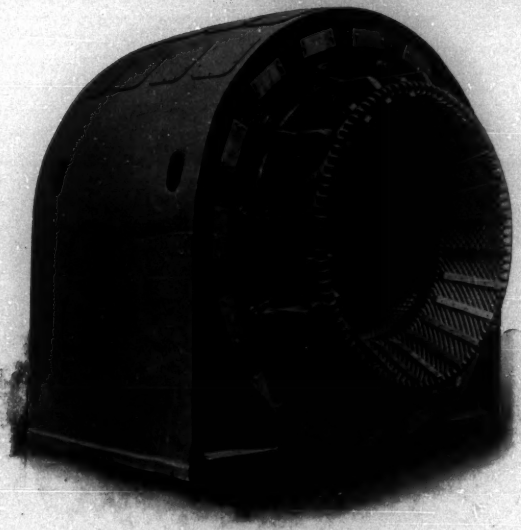


FIG. 21 [LAMME]

peripheral speed of 408 ft. (124.3 m.) per second, or approximately 24,500 ft. (7468 m.) per minute. The core is designed for a very considerable margin of safety, and is actually tested at overspeeds which give practically 30,000 ft. (9144 m.) peripheral speed at the surface of the core.

In certain 19,000-kv-a., 62½-cycle, four-pole, 1875-rev. per min. machines now being built, which are of the radial-slot rotor construction, the rotor diameter is 49 in. (124.4 cm.). This gives a peripheral speed of 24,000 ft. (7315 m.) per minute. This compares with a speed of 21,600 ft. (6583 m.) in a 21,000-kv-a. two-pole, 1500-rev. per min., 25-cycle, radial-slot machine also being built, the rotor core of which is shown in Fig. 12. Obviously the mechanical limitations are being more closely approached in the 60-cycle machines, up to the present capacities.

If a comparison is made between the above 5000 and 19,000-kv-a. rotors, with their parallel and radial type constructions, it is found that their limitations lie in quite different features. In the radial-slot type, the core stresses are much lower than in the other, but the supporting end ring is an important problem, requiring for its solution a very high grade of steel for the material of the ring. In the parallel-slot rotor, the maximum stresses are in the core itself, principally in the parts which overhang the slots at the sides and ends of the core. In the radial slot core, there are no such overhanging masses. In both constructions, the core material is purposely made of relatively soft steel, having a high percentage elongation, the object being to obtain a material which can yield sufficiently to transfer the strains from local higher points, to adjacent lower parts, and thus equalize them, to a great extent.

The smaller diameter rotor cores are made of steel forgings, in one piece. The larger cores are made up of thick steel plates assembled and bolted together to form a solid mass comprising the core and shaft extensions. By this disk construction, commercial material is used which is of uniform quality clear to the center of the disks. The fiber of the material is in a direction best suited to the directions of stress. With corresponding size cores made in one piece, the outside, to a certain depth, can be given fair physical characteristics, but the center is liable to be glass-hard, as found by experience. However, this may not be a prohibitive condition in machines of more moderate peripheral speeds. Herein lies one great difference between American and European limitations. In American practise, 60 cycles,

calling for 3600 and 1800-rev. per min. machines, is the standard frequency, while in Europe, 50 cycles is standard, giving 3000 and 1500-rev. per min. machines. These lower speeds make an enormous difference in the possibilities of design and construction.

Present Limitations in Design

On account of the very great capacities, at high speeds, now being obtained in turbo-generator practise, a number of problems are being encountered, the solutions of which are producing more or less radical changes, both in design and in practise. Some of the limitations now encountered are in the relatively high temperatures in certain parts, high losses in a relatively small space, the difficulty of ventilation, due to the requirement of enormous volumes of cooling air through limited openings or passages, the type of insulation, fire risks, regulation and short-circuit conditions, etc.

A number of these limiting conditions, such as the temperature, ventilation, losses, and insulation, are so closely related to each other that it is difficult to describe any one of them in detail, without including the others to a considerable extent.

The Problem of Ventilation

In the general problem of ventilation, four conditions must be considered, namely, the total loss, or heat, developed, the surface exposed for dissipating this heat to the air, the quantity of air required to carry away the heat, and the temperature of the cooling air.

In the conduction of heat from the surface of a body into the air, the quantity of heat per unit area which can be dissipated depends upon the difference in temperature maintained between the surface of the body and the body of air to which the heat is conducted. The heat dissipated raises the temperature of the adjacent air a certain amount, and thus tends to reduce the temperature difference, unless the air is renewed with sufficient rapidity. On the other hand, if the quantity of air is so great, in proportion to the heat dissipated, that there is but little rise in the air temperature, then any increased amount of air over the surface will represent practically no gain in ventilation. In other words, when the amount of air passed over a surface is sufficient to take up the heat dissipated from the surface without an undue rise, then a further quantity of air is wasteful, and it may even be considered as indirectly

harmful, in those cases where the total quantity of air is limited. This has a direct bearing on the size of ventilating ducts or passages in a machine. If the air path through a duct is relatively long, then a considerable width of duct may be required in order to get the necessary quantity of air through it. On the other hand, if the air path is very short, then a very narrow duct may be most effective, for a wider duct may allow more air to pass through than can be utilized in taking up the heat.

No matter how thoroughly the ventilating air is distributed through the heat-generating body, or however effective the heat-dissipating surfaces may be, the total air supplied must be ample in quantity, or its temperature will be raised an undue amount. As the surfaces to be cooled must always have a higher temperature than the cooling air, any considerable rise in the latter will have a direct influence on the ultimate temperature which may be attained by the body to be cooled. Conversely, if an ample quantity of cooling air is supplied, but the heat-dissipating surfaces are insufficient, the ultimate temperature of the body will also be affected.

In large capacity, high-speed turbo-generators, the problem of ventilation is one of the most difficult ones encountered. The trouble lies principally in the large total loss expended in a very limited space. The difficulties of the problem may be illustrated by the following example:

Assume, in a 1500-rev. per min., 25-cycle, 15,000-kv-a. machine, a total efficiency of 96.5 per cent, including air friction loss inside of the machine. This means a total loss in the machine of 545 kw., which is not excessive for this capacity, but is very large for the limited space in which it is developed. A very large volume of cooling air is required for carrying away the heat due to this loss. A simple approximate rule for determining the quantity of air required is that an expenditure of one kw. in one minute will raise the temperature of 100 cu. ft. (2.8 cu. m.) of air 18 deg. cent. Therefore, 545 kw. loss would require a supply of ventilating air of approximately 50,000 cu. ft. (1416 cu. m.) per minute for a rise of the outgoing air of 20 deg. above that of the incoming air. Assuming a velocity of 3000 ft. (914 m.) per minute, this would mean, with a cylindrical ventilating channel, a diameter of 56 in. (142.2 cm.), which is greater than the rotor diameter itself. However, as the cooling air ordinarily would be supplied to both sides of the machine, the ventilating passage need only be half the above section for each side.

Obviously, such passages are prohibitively large, and much greater air velocities through the machine proper are necessary. Velocities as high as 5000 to 6000 ft. (1524 to 1828 m.) per minute are common, while, in some cases, more than 10,000 ft. (3048 m.) per minute has been required in certain constricted sections of the air path inside the machines. Therefore, no matter how the problem is considered, it may be seen that the above condition of the enormous volume of air required, makes the problem of ventilation a difficult one.

There are several methods of ventilating large turbo-generators, depending upon the system of applying the air. There is, first, the radial system, in which practically all the cooling air passes out radially through ventilating ducts in the stator core. This radial system of ventilating can be subdivided into two alternative methods, depending upon whether the air is partly or wholly supplied through passages in the rotor, or through the air gap alone. These two methods are illustrated in Fig. 13. The straight air gap arrangement may require a relatively large air gap, combined with very high velocity of the air along the gap, while the other method permits a considerably shorter gap. The straight air gap method of ventilation is used, to a considerable extent, in all 60-cycle machines of two-pole construction, while it is practically the only one that has been used with the parallel-slot type of machine with either two or four poles. In this parallel-slot type of rotor, however, the air gap can be relatively larger than the radial-slot type of rotor, as explained before, which compensates, to some extent, for the necessity of depending upon this method entirely. In the four-pole parallel-slot rotors, the interpolar spaces are also effective. Moreover, with parallel-slot rotors in general, the openings from the air gap into the stator ventilating ducts can usually be somewhat larger in total section than with the radial type of rotor, as also described before. However, the relatively greater axial length of the core of the parallel-slot type of rotor increases the length of the constricted air passages along the air gap in the two-pole machines, which is a material disadvantage.

The straight air gap type of ventilation has proved astonishingly effective in cooling the rotor in both the radial and parallel-slot types of rotors, and with either type there is usually no great difficulty in forcing through enough air to cool the rotor core in a fairly effective manner. It must be considered, however, that the total rotor loss in large turbo-generators is possibly

only 10 per cent of the total loss which must be taken care of, and a relatively small proportion of the total ventilating air may suffice to cool it. According to actual measurements, corroborated by general experience, the cylindrical surface of the rotor core can give off four or five watts per square inch (6.45 sq. cm.) to the cooling air, with a temperature rise of the rotor surface of about 35 to 40 deg. cent. above the cooling air. To those who have had experience with dissipating heat from electric apparatus, this result will appear to be extremely good.

The real difficulty with the air gap method of ventilation is not so much in getting enough air through for cooling the

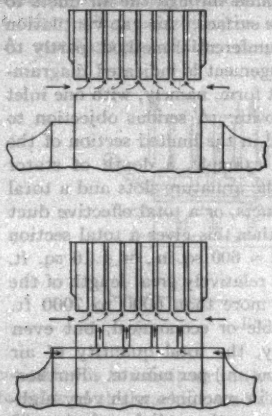


Fig. 13

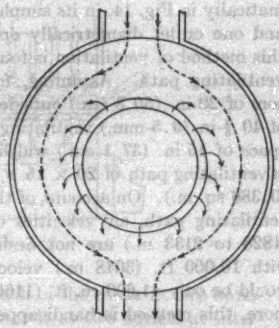


Fig. 14

rotor itself, but it is in the much larger quantity required for the stator. For instance, a one-inch (2.54-cm.) depth of gap (from iron to iron) with a 50-in. (127-cm.) diameter of rotor, means a total section of air path into the gap (counting both ends of rotor) of 314 sq. in. or 2.18 sq. ft. (0.19 sq. m.). At a velocity of 10,000 ft. (3048 m.) per minute, this allows a flow of only 21,800 cu. ft. (617 cu. m.) per minute, which will not take care of a large machine, from the present standpoint of possible capacities with the above diameter of rotor. By additional openings in the rotor core, this might be increased to 30,000 cu. ft. (849 cu. m.) per minute, but even this is still

much less than a machine with a 50-in. (127-cm.) diameter of rotor would require if built for capacities otherwise possible. Therefore, on account of this limitation in the amount of cooling air, other means of ventilation have received much consideration. Two other general systems of ventilation, in addition to the gap method, have been used, namely, the circumferential method, and the axial. The former has been developed and applied more extensively in the past, but the latter contains possibilities which are bringing it rapidly to the front.

In the circumferential method of ventilation, air is supplied to one or more points on the outside circumference of the stator, and is forced circumferentially around through the air ducts to suitable outlets, also on the outside surface. Air gap ventilation is usually combined with this circumferential method, partly to cool the rotor. The general arrangement is indicated diagrammatically in Fig. 14, in its simplest form, namely, with one inlet and one outlet diametrically opposite. A serious objection to this method of ventilation is found in the limited section of the ventilating path. Assuming, for example, a depth of stator core of 20 in. (50.8 cm.) outside the armature slots and a total of 40 $\frac{3}{8}$-in. (9.5-mm.) ventilating ducts, or a total effective duct space of 15 in. (37.1 cm.) width, then this gives a total section of ventilating path of $20 \times 15 \times 2 = 600$ sq. in., or 4.16 sq. ft. (0.386 sq. m.). On account of the relatively great length of the ventilating path, air velocities of more than 6000 to 7000 ft. (1828 to 2133 m.) are not desirable or economical, but even with 10,000 ft. (3048 m.) velocity, the total quantity of air would be only 41,600 cu. ft. (1166 cu. m.) per minute. Furthermore, this method is handicapped in machines with very high-speed rotors, by interference between the radial and the circumferential systems of ventilation, so that the full benefit of either is not obtained. Below a certain rotor velocity, apparently the circumferential action can predominate, and the method is fairly effective up to the permissible air capacity of the stator ducts; but at very high speeds the radial ventilation may very seriously interfere with the other, so much so, that the radial ventilation alone, even with its very restricted gap section, may give as good results as the two methods acting together.

To avoid this interference, various methods have been devised, such as closing part, or all, of the radial ventilating ducts at the air gap to keep the radial effect from interfering with the other. One arrangement which has been used in Europe to a considerable

extent is indicated in Fig. 15. In this, the alternate radial air ducts are closed at the outside surface, while all are closed at the air gap. The air enters by the ducts open at the back of the machine, flows both circumferentially and toward the gap, and crosses over to the intermediate ducts by axial openings back of the armature teeth, and then along these ducts to the outlet. This scheme is effective in principle, but is uneconomical in the sense that less than the total section of stator ducts is useful, as regards the quantity of air which can be carried. There is usually one large central duct to allow an outlet for the rotor ventilating air. This particular arrangement of the stator also uses axial ventilation in crossing over from one set of ducts to the other, which is an effective arrangement.

A modification of the simple circumferential method of

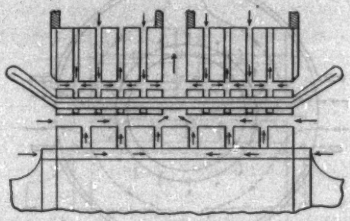


FIG. 15

ventilation is to admit air to the back of the stator at two opposite sides of the machine, and deliver it at two outlets at intermediate points on the surface, as shown diagrammatically in Fig. 16. By this means, the cross-section of the ventilating path is doubled and the length is halved. Also, the interference of the radial ventilation with the circumferential will be less harmful. A serious disadvantage in the circumferential ventilation in general is that the ventilating path is relatively long, especially where there is but one inlet and outlet, and therefore the cooling air at the outlet of the channel may be considerably hotter than at the inlet, with consequently less effective cooling action. This means points of local higher temperature in the core, due to the method of ventilation. In the radial type of ventilation, the coolest air is applied near the seat of the highest losses, namely, at the armature teeth, and immediately back of

them, and the air, as it becomes heated, passes over the outer part of the iron which has a diminished loss, and therefore normally less heat to dissipate. Therefore, the effect of the increased temperature of the cooling medium is offset by the lower loss, and consequent less necessity for ventilation, in the part where the air is hottest. The radial system of cooling is therefore theoretically the most effective, but practically, the difficulty is in applying it, due to the limited air passages available.

Both the circumferential and the radial methods of cooling are subject to one serious defect, namely, most of the generated heat in the stator iron must be conducted across the laminations to the air ducts. The rate of conduction across the lamina-

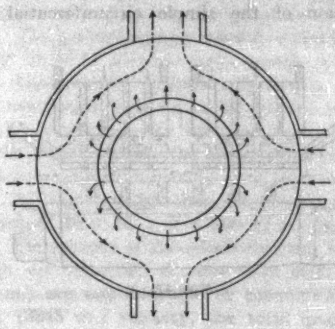


FIG. 16

tions is only from 1 per cent to 10 per cent as great as along the laminations themselves, according to various authorities. Therefore, if the heat could all be conducted along the laminations to the ventilating surfaces, apparently much more effective heat dissipation could be obtained, provided sufficient surface is exposed to the air, and an ample quantity of air supplied. This has led to the development of the axial system of ventilation, as distinguished from the radial and circumferential. In this method, numerous axial holes are provided in the stator core which may extend uninterruptedly from one side of the core to the other, or they may extend from each side to one or more large central radial channels which form the outlet. The usual numerous radial ducts are omitted, or may be con-

sidered as combined in one central channel. This general arrangement is illustrated in Fig. 17. The rotor cooling is accomplished by air along the air gap, and through the rotor core to the large central duct. In this method of ventilation, therefore, there is a combination of two types, namely, the axial and the air gap, but there is not the interference between the two that is sometimes found where the circumferential method is used.

From the preceding, it may be seen that the problem of putting a sufficient quantity of air through the machine is an extremely difficult one. In addition, in very large machines, the problem of supplying the required quantity of air from a suitable blower forms another serious problem. In smaller capacities, and in slower speed machines, it has been the usual practise to attach blowing fans to the rotor shaft or core, as

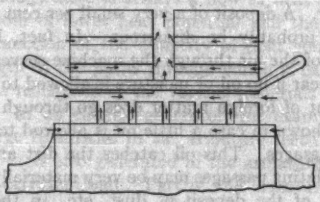


FIG. 17

part of the outfit. There is no particular difficulty in this arrangement, except, possibly, in the high-speed construction of the fans required for 60-cycle, two-pole machines. Such fans can supply an amount of air which is limited by the diameter and other dimensions of the fan itself.

Assume, for example, that by lengthening the rotor core, or by other modifications in the construction, the capacity of the machine can be doubled, and therefore double the quantity of air is required for cooling. If the limit of the fan design or operation was reached before, then obviously some radical change is required with the new capacity of the machine. This condition apparently has been reached in some of the later practise in large, high-speed turbo-alternators. One obvious solution of this difficulty lies in the use of separate lower-speed, large diameter, fans or blowers. This may appear to be a step backward, but when the above conditions and limitations are

taken into account, it is not so. The "tail" must not be allowed to "wag the dog;" the blower, which is an adjunct, must not be allowed to dominate the construction of the machine itself. Moreover, there are a number of meritorious features in the use of a separate blower. In the first place, it can be made somewhat more efficient than the high-speed, rotor-driven fans. Again, with a suitable means to drive, variable speeds, and therefore different air pressures, can be obtained. This feature may prove to be very desirable or advantageous under peak, or overload, or emergency conditions.

One further condition keeps cropping out in the general problem of ventilation, namely, that of filtering or washing, or otherwise cleaning the ventilating air. With 50,000 to 75,000 cu. ft. (1415 to 2122 cu. m.) of air per minute passing through a large machine, obviously in a year's time an enormous quantity of foreign matter is carried through the machine with the ventilating air. A deposit of a very small per cent of this in the machine will probably be disastrous. In fact, however, the high velocity of the air through the machine serves to keep the air passages clear if no oil or moisture is allowed to enter. That a large amount of foreign matter does go through the machine is very soon shown in case a little oil is allowed to get into the ventilating passages. This oil catches the dirt and in a short time the ventilating passages may be very materially obstructed.

On account of the deposit of dust, etc., in the ventilating passages, it is necessary to clean certain types of machines at more or less frequent intervals, and it is advisable to clean all types occasionally. With some systems of ventilation, where such cleaning is difficult, or almost impossible, such as that shown in Fig. 16, provision must be made for cleaning the air before it enters the machine. With the particular construction shown in Fig. 16, air filters are almost always supplied. In the American types of construction, however, such filters have not yet been used, except in a more or less experimental manner, due probably to the greater accessibility of these machines as regards cleaning. But such filtering processes possess considerable merit in general. One modification which is being agitated at present is that of washing, instead of filtering, the air. This serves the double purpose of cleaning and cooling the air, and in very hot weather, when the available capacity of the machine is at its minimum, this cooling effect may mean a reduction of 6 to 10 deg. in the temperature of the machine.

The Temperature Problem

In the general problem of temperatures in electrical apparatus, it is not the rises, but rather the ultimate or limiting temperatures which are of first importance. Furthermore, the real limitation in ultimate temperature does not lie in the copper and iron, but in insulating materials used; and only insofar as the temperatures of the former affect the latter do they concern the general problem. However, as insulating materials in themselves are not usually sources of heat, but as they receive most of their heat from adjacent media, such as iron or copper which may be generating loss, the real temperature problem, as regards insulation, resolves itself into the consideration of that of the adjacent materials. Therefore, it is one which, for its full analysis, requires a knowledge of the sources and amounts of heat generated, and its conduction and distribution to other parts.

Broadly speaking, there is always a flow of heat from points of higher to those of lower heat potential and the amount of flow is also a function of the quantity of heat generated, the section and length of the paths through which it can flow, and the specific heat resistance of the various materials which conduct the heat. In an electric generator, for example, heat is generated in large quantities in the armature teeth and in the armature core. It is also generated in the armature coils when the machine is carrying load. Part of the armature copper is buried in the armature slots where it is almost surrounded by iron, which, in itself, develops a loss, while another part, such as the end windings, may be surrounded by, and thoroughly exposed to, the ventilating or cooling air. In such end portions, the flow of heat will usually be from the inside copper, directly through the insulation to the cooling air. The amount of heat which will flow from the copper through the insulation, depends upon the temperature differences between the copper and the outside surface of the insulation, upon the cross-section of the path of flow, upon the thickness and "make-up" of the material, and upon the heat-conducting properties of the insulation itself. There is also a considerable temperature gradient from the outside surface to the air. If the surrounding air is not renewed with sufficient rapidity, the flow of heat from the insulation to the air may raise the temperature of the adjacent air, so that the total temperature drop is decreased, and the amount of heat dissipated is correspondingly reduced.

In the armature core, the problem is much more complex.

In the copper buried in the armature slots, there are usually three paths along which the heat can flow: First, it may flow from the copper directly through the insulation to the iron, provided the adjacent iron temperature is lower than that of the copper. Second, it may flow lengthwise of the copper to the end windings to be dissipated directly into the air from that portion of the winding, as described above. Third, in the case of open-slot machines, one edge of the coil may be exposed to the air in the air gap, and there may thus be a direct conduction of the heat through the insulation to the air in the air gap. This latter case, however, only holds for the upper coil, or that next to the gap, in the case of two coils per slot, which is the most common construction. In the bottom coil, the only means of conduction in the buried portion of the coil, are to the adjacent iron or lengthwise to the end windings, or to the adjacent upper coil, which, however, would normally have at least as high temperature as the lower coil. Therefore, the two effective paths should be considered as through to the iron and thence to the air, and lengthwise of the copper to the end windings and to the air. It is the relation of the various factors of these two paths that control the actual temperatures.

It has usually been considered that, in the buried copper, the greater portion of the heat is conducted directly into the surrounding iron. This, however, is only partially true, depending upon many features in the construction and type of apparatus. The heat conductivity of copper is, roughly, about six times that of laminated iron lengthwise of the sheet, which is possibly ten to twenty times as great as across the laminations. In an armature which is comparatively narrow and which has very open, well ventilated end windings, a relatively small difference in temperature between the copper at the center of the core and that in the end windings, may cause a relatively large flow of heat from the buried copper to the end copper. Therefore, in certain designs, a great part of the armature copper heat may be dissipated through the end windings, and not through the armature core, especially in those cases where the armature core in itself has a considerable temperature rise. There might even be no conduction of heat from the copper to the iron, or there may be conduction from the iron to the copper; for if the copper is at the same temperature as the iron at the center of the core, for instance, then at each side of the center, or as the edges of the core are approached, the copper temperatures will be relatively

lower than at the center, and therefore lower than the adjacent iron, on the assumption that the iron temperatures would be practically constant over the full width of the core. The conditions would therefore be as represented in Fig. 18. The solid line *a* in this figure represents the iron temperature at uniformly 40 deg. cent. rise, and the dotted line *b* represents the copper temperatures from the center of the core to the edges. The temperatures at the center being assumed the same for copper and iron, obviously there will be a flow of heat from the iron to the copper near the edges of the core. The effect of this additional heat carried out by the copper would be such as to tend to increase the temperature of the copper at the center of the core by "banking up" the copper heat.

Again, if the temperature of the copper at the center is materially higher than that of the surrounding core, the conditions may be as represented in Fig. 19. In this case, assuming the core at constant temperature, there will be heat flow from the copper to the iron at the center of the core, and from the iron to the copper at the edges.

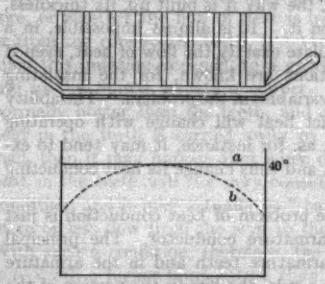


Fig. 18

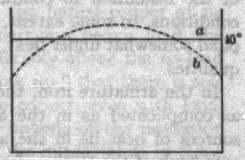


Fig. 19

This study of the problem leads to certain very curious conditions which are sometimes found in large machines. At no-load, for instance, with practically no copper loss present, and with high iron loss, there may be a very considerable flow of heat from the armature teeth through the insulation into the copper, and thence to the end windings and to the air. In this way the temperature of the armature teeth at no-load, and with normal voltage generated, may be considerably reduced by conduction of the iron heat into the copper, while the copper itself

may show a very considerable temperature rise. When load is placed upon such a machine, sufficient to raise the temperature of the copper up to that of the iron in the armature teeth, the latter is actually increased in temperature, due to the prevention of the heat conduction into the copper. In this way, therefore, the copper may apparently heat the iron, although there is no direct flow of heat from the copper to the iron, but the reverse flow is prevented.

In high-voltage windings requiring thick insulation, the temperature drop from the copper to the outside may be relatively large; that is, with a given difference of temperature between the copper and the surrounding air, a relatively small amount of heat may be conducted through the insulation. Experience shows that the amount which can be conducted is a function of the quality of the material, the way it is built up, its thickness, and also the pressure upon it. It is almost impossible, in a machine in service, to calculate exactly the flow of heat, even if all the temperature conditions are known, for the insulating material itself is one of the variables in the problem. The ability of the insulation to conduct heat will change with operating conditions, to some extent, as, for instance, it may tend to expand somewhat under heat, and thus change its heat conducting qualities.

In the armature iron, the problem of heat conduction is just as complicated as in the armature conductor. The principal sources of heat lie in the armature teeth and in the armature core back of the teeth. As a rule, the loss in the portion of the core immediately back of the teeth is relatively greater than at a greater depth, for the magnetic fluxes, which cause the temperature rise, generally crowd close to the teeth, so that the density is higher at such parts.

The heat from the armature teeth can be dissipated along several paths. It can flow lengthwise of the laminations to the end of the tooth and into the air gap, where the ventilation is usually fairly good, but the tooth surface exposed is relatively small. In the second place, it can flow back along the laminations to the armature core where it can spread out through a path of much greater cross-section and be conducted partly to the back part of the laminations, and partly transversely to the ventilating ducts. A third path from the armature teeth is across the laminations of the teeth, to the neighboring ventilating ducts. This latter path, however, must necessarily be relatively poor

in conductivity per unit section of path, compared with the others, but offsetting this, it is frequently of much greater cross-section and of relatively small length. In passing from plate to plate, the heat must pass through the insulating varnish, or other material used, which is of relatively high heat resistance compared with the iron itself. Nevertheless, in machines with radial ventilation, a very considerable portion of the heat due to the tooth loss is carried transversely through the plates to the air in the ventilating ducts, simply because that is the path of lowest total heat resistance, everything considered. In many cases, the temperature in the core back of the teeth may be as high as that of the teeth themselves, so that the only flow possible is across the laminations to the air ducts, or lengthwise to the tip of the teeth in the air gap. Therefore, the question whether the armature teeth may be hotter than the armature core, or whether the flow of heat is from the teeth to the core, or from the core to the teeth, is a very involved one; and yet upon this question depends, to a great extent, the temperature rise in the buried armature copper. If the armature core is normally hotter than the teeth, and a considerable amount of heat in the teeth is carried away by the buried copper at no load, then it may happen that when carrying heavy load, the heat in the teeth will rise very considerably above the no-load condition, and it may actually so "bank up" that there is still more or less flow from the iron to the copper, even with load. With such a condition, therefore, the outside of the insulation may reach a higher temperature than the inside, while in those cases where the temperature of the copper rises above that of the iron of the armature teeth, the inside of the insulation will be hotter. Therefore, the temperature to which the insulation is liable to be subjected appears to be largely a problem for the designer to determine from his calculations, based upon accumulated data and experience. This is especially the case with very wide armature cores and large, heavily insulated armature coils, such as found in large capacity, high-speed turbo-generators. In such machines, experience has shown that various temperature conditions may be found, depending upon the location and relative values of the losses in the different parts and the means for conducting away the heat. Tests have shown that, in some cases, the armature iron at the center of the core is considerably warmer than the armature copper, while in other cases the opposite is found to be true.

In such apparatus, the temperatures actually obtained are liable to be materially higher than the usual methods of measurement will indicate. These temperatures are inherent in the conditions of design and cannot be avoided economically, in certain types of apparatus, such as turbo-generators. In such machines, the limitations in speed, strength of material, etc., force the designer to certain proportions which preclude larger dimensions, or lower inductions in the iron, or lower densities in the copper, or increased ventilation. In such apparatus, therefore, the development apparently lies in the direction of insulations which will stand the higher temperatures which may be obtained.

These conditions of higher temperatures in some parts of the machine than indicated by the usual tests, have been recognized for years by designers and manufacturers of large electric machinery. A rough indication of these temperatures can be obtained by exploring coils or thermocouples suitably located. However, it is evident that such coils, if located next to the copper, will not give the correct temperature measurement if the flow of heat is from the iron to the copper, while a coil next to the iron will not give the correct result with the flow from the copper to the iron. Experience has shown that the temperatures, in corresponding positions around the core, may not be uniform, due to local conditions. In consequence, it is not practicable to actually determine the true temperatures of all parts of the insulation on commercial machines, except by measurements of a laboratory nature, which would involve such a number of separate readings as to be commercially prohibitive.

On account of the higher temperatures which may be found in such apparatus, and the difficulty of making exact measurements, except by laboratory methods, manufacturers very generally have adopted the use of mica as an insulating material on the buried part of the coils. Experience has shown that such material, when properly applied, can safely stand temperatures of at least 125 deg. cent. How much more has not yet been determined.

Of such machines it may be said that the manufacturer, with his guarantee of 40 deg. cent. by thermometer, actually builds for possible temperatures of 70 to 90 deg. cent. in some parts of the machine, for he expects to find fairly high temperatures in some cases with exploring devices. The usual guarantee of 40 deg. cent. therefore should be considered as only a relative indication of a safe temperature in such apparatus.

If, for instance, the exploring coils should show 70 deg. cent. maximum rise under running conditions, and the permissible ultimate temperature of fibrous or tape insulation is assumed as 90 deg. cent. for continuous operation, then obviously, with air at 40 deg. cent. the insulation would be considered as insufficient from point of durability, except for intermittent service, such as overloads, and such limited conditions. Plainly, the insulation, for such temperatures, should be of mica, or equivalent material, for which 125 deg. cent. has been found to be safe.

Furthermore, it may be stated that with such mica insulation, a turbo-generator which shows 75 deg. cent. rise by exploring coils, or thermocouples, has, in fact, more margin of safety than the ordinary varnished-tape-insulated low-voltage machines of any type, which show 40 deg. cent. rise by thermometer or 50 deg. cent. rise by resistance.

The foregoing aims to bring out clearly that the temperature problem is a most complex one, in all electrical apparatus, and especially so in turbo-generators. It indicates that no simple temperature test can show all the facts, and that all commercial methods must be considered as approximations. It also shows the absurdity of classifying a piece of apparatus as *good* or *bad*, respectively, according to whether it tests possibly one or two degrees below or above a specified thermometer guarantee. Also, following out the above principles on heat flow, various fallacies in temperature measurements might be noted. For example, it is usually assumed that, after shut-down, if a gradually rising temperature is shown, this is a more accurate indication of the true temperature. But this may be entirely wrong as regards windings. If, for instance, the core back of the armature slots is materially hotter than the armature teeth while carrying load, then, upon shut-down, with the air circulation stopped, the teeth will rise to approximately the same temperature as the core back of the teeth, and there may be a flow of heat into the coils, which condition may not have existed while carrying load. A thermocouple on the coil or in the teeth would thus indicate a false temperature rise after shut-down. This is cited simply as one of many instances, to show the possibilities of entirely wrong conclusions which may be reached in the problem of temperature.

The Insulation Problem

The one fundamental condition which must be considered in the insulation problem is the durability of the material itself, and

this must be viewed from two standpoints—the mechanical, and the electrical. From the mechanical standpoint, the material may have its insulating qualities impaired by the action of mechanical forces which tend to crack, or crush, or disrupt the material itself, or it may be affected by being permeated by foreign materials or substances, or it may be injured by such overheating as will partially or wholly carbonize it, or render it brittle or otherwise unsuitable for the desired purpose.

From the electrical standpoint, it may be weakened by deterioration of the quality of the insulating material itself or some of its component parts, which may be due to heating, or oxidation, or many other causes.

The effect of mechanical injury, such as cracking, crushing or overheating, on the insulating qualities, will depend upon many conditions. In some cases, with relatively low voltage, any effective mechanical separation of the parts is sufficient for electrical purposes. For higher voltages, continuity of the separating insulating medium is necessary.

Experience has shown that, for moderate voltages, temperatures which may injure, or even ruin, the insulating material, from a mechanical standpoint, may not seriously affect its insulating qualities. Many insulating materials of a cellulose nature will still retain good insulating qualities if maintained at temperatures as high as 150 deg. cent. for such long periods that the material itself semi-carbonizes. Under such high temperature conditions, however, it becomes structurally bad—that is, it may become so brittle that it tends to crumble, or powder, or flake off, and thus its value as an insulation is impaired by displacement of the material itself. In low voltages, therefore, it is not a deterioration in the insulating qualities, but rather a mechanical breakdown of the material itself, which is liable to cause trouble. With high voltages, however, the conditions may be quite different. With some insulating materials, the dielectric strength may be so affected by long continued high temperatures that the insulating quality becomes insufficient. This has a direct bearing on large capacity, high-voltage tubo-generators.

In the problem of insulation, certain difficulties have been encountered in large turbo-generators, which, while they would have developed eventually in other large machines, yet became apparent more quickly and prominently in the turbo type, due to the abnormal conditions in its design. The two most promi-

nent difficulties were, first, that of relatively high temperature in the buried copper, already described, and second, the destruction of the insulation by reason of static discharges between the coils and the armature iron.

Due to the fact that the ultimate temperature reached in such machines not infrequently exceeds the safe limits for insulation of the fibrous or cellulose type, such insulations will show deterioration eventually in their insulating qualities and their durability. In consequence, with the advent of the larger machines, it became necessary to return to the use of mica for insulating purposes on the buried part of the coil. This type of insulation, in the form of mica wrappers, had been used extensively on some of the earlier large capacity, low-speed generators, but it had not been adopted on large turbo-generators, due principally to the difficulty in applying the very long wrappers for the straight part ot the coil. However, when the gradual deterioration of the fibrous type of insulation was noted in large turbo-generators, the mica wrapper type of insulation was again taken up and, after considerable experiment, was applied successfully for the outside insulation on the straight parts of the coils. This use of mica overcame the deterioration in the insulating qualities of the outside insulation; but for a while it was considered that a fibrous type of insulation was still effective between turns in those coils where there were two or more turns in series per coil. As stated before, the insulating qualities of many fibrous materials will stand up astonishingly well under low voltages, when the material is apparently so greatly heated that it is practically carbonized. Therefore, temperatures which did not carbonize, but simply browned, or darkened, the material, had not been considered dangerous, and undoubtedly many thousands of electrical machines of all kinds are today in operation, in which the insulation is in this condition, and in which no trouble need be expected. For this reason, little or no trouble was expected between turns on the turbo-generators. However, a new condition was encountered in large capacity machines, namely, the insulation between turns, when it became dry and brittle at the higher temperatures, was liable to be injured by the terrific shocks to which the coils were subjected in such machines, in case of a short circuit across the terminals. The insulation would be cracked, or so disturbed that short circuits would occur later, without apparent cause. These short circuits on large machines

most often appeared as breakdowns to ground, even with the mica wrapper insulation on the outside of the coil. Incidentally, several cases were discovered where arcs had occurred inside the coils between adjacent turns, and where they had not yet broken through the outer insulation to ground. For many months the writer, with his associates, followed up this matter, examining all available coils and windings. Eventually the conclusion was reached that many of the breakdowns to ground had actually started between turns on the inside of the coil. Moreover, as a corroboration, it was noted that in machines with one conductor per coil the breakdowns were practically negligible. This investigation led to the practise of insulating the individual turns, in each coil, from end to end, with mica tape. After the adoption of this practise, it is noteworthy that the breakdowns to ground practically disappeared, although the outside insulation to ground had not been changed in type or thickness.

Many improvements have been made in recent times in the application of this mica insulation. One of these is the Haefely process, developed in Europe, but now being used extensively in this country. By this process, the mica wrappers are so tightly rolled on the coil that practically a solid mass of insulation, of minimum thickness and greatest heat conductivity, is obtained.

By means of the mica insulation, the temperature difficulties in general have been entirely overcome, and a durable and non-deteriorating construction, from an insulation standpoint, has been obtained with the temperatures which appear to be more or less inherent in the large, high-speed turbo-generators.

The second trouble, namely, that due to static discharges between the armature copper and the iron, was also encountered to a certain extent on some of the earlier machines. It was found that these discharges were apparently "eating" holes, or even grooves, through the outside insulation of the armature coils. This effect was most pronounced at the edges of the air ducts and at the ends of the armature core, where edges were presented by the iron. After a long period, the holes or grooves would become so deep that the insulation was weakened or ruined.

This was a very disturbing condition, when it was once fully recognized and appreciated. Again, a comprehensive investigation was made to discover a cure for this difficulty. Various types of machines and windings were examined. It was noted

that the action was a function of the voltage of the machine, but was noticeable, in some cases, at relatively low voltages. During the course of the investigations, it was noted that where mica wrappers were used with an outside layer of tape, the "eating away" extended only through the outside wrapping in as far as the mica, and that no apparent effect at the mica was visible. Even when examined with a very powerful microscope, no evidence of any puncture of the mica was found, in any case. These investigations naturally led to the conclusion that the most suitable remedy for the trouble was the use of mica insulation, which was also a remedy for the temperature conditions. This is one of the rare cases in large turbo-generators where two desirable conditions do not conflict with each other. The mica insulation on the buried part of the coil has now been very generally adopted in this country on high-voltage machines, whether of the turbine-driven, or any other type.

This static trouble was considered so serious at one time that low-voltage practise with step-up transformers was adopted by some manufacturers as the safest course, until something positive in the way of a remedy was proved out. This trouble promised to be one of the most serious encountered in high-voltage generator work, and even threatened to revolutionize practise in winding generators for the higher voltages. However, as consistently advocated by the writer, the use of mica, suitably applied, appears to have entirely overcome this trouble, as evidenced by several years' experience, and all indications now are that there need be no fear of static discharges on windings of 11,000 and 13,000 volts. Even in the 11,000-volt New Haven generators with one terminal grounded, which gives the equivalent of a 19,000-volt, three-phase winding with the neutral grounded, the mica insulation appears to be successful and durable.

Rotor Insulation

In most of the early turbo-generators, the rotor winding in the slots was insulated with fibrous material, "fish paper" and "horn" fiber having the preference. One of the difficulties in the rotor is that the insulation between the winding and the slot is liable to be crushed or cracked by the high centrifugal forces. In the earlier insulations, before fish paper was used, it was found that even at very moderate temperatures the insulation got dry and brittle, and cracked readily. Fish paper, or horn fiber, was then adopted pretty generally. Such material

apparently stood much higher temperatures than the ordinary fibrous insulations. However, experience also showed that eventually this also became brittle, and was liable to be cracked, and then displaced, due to the centrifugal forces. There is always the possibility of a small amount of movement in the field coils when a machine is being brought up to speed, and this movement, in itself, may eventually damage the insulation if it is at all brittle.

As the capacities and speeds of turbo-generators were increased and the space limitations for the rotor windings became more pronounced, the resulting higher normal temperatures led to the adoption of mica for the insulating material in the slots with either mica or asbestos for the insulation between turns. As the voltage between adjacent turns is always extremely low, what is needed is really a durable separating medium, rather than an insulation, this medium being one which will not become crisp or brittle at fairly high temperatures. Asbestos has served for this purpose very effectively, and even has some advantages over mica, as the latter must be applied in relatively small pieces in the form of strap or tape, and the individual pieces are more readily displaced or shifted than is the case with asbestos. Some very severe tests have been made in order to determine the possibilities of such rotor insulation. In one case, a turbo rotor thus insulated was run at full speed for over 40 hours, with such a current that the rise by resistance in the rotor copper was about 250 deg. cent. It was the intention to continue this test very much longer, but the conduction of heat from the winding to the core, and thence through the shaft to the bearings, was such that finally the bearings became overheated and gave out. After this test, the winding was carefully dismantled, and no evidence of any injury to the insulation could be discovered. Of course, such temperatures are not recommended in turbo rotor practise, but this was simply an attempt to find a temperature limitation. If a designer wants to find the facts in any apparatus, he will obtain the most valuable information if he operates the apparatus up to the point of destruction. He thus fixes a limit which he must keep below.

The use of mica, or mica and asbestos, on turbo rotors has been very generally adopted in this country at the present time, and it may be said that, within the writer's experience, no case of destruction of one of these windings through heating has

come to his notice, although a great number of them have been in service for a relatively long time. In many of the older machines with fish paper insulation in the rotors, the conditions of ventilation and the normal ratings of the machines were such that the maximum temperatures in the rotor windings were relatively much less than in present practise. It may therefore be said that the use of mica in the rotor has been largely due to the introduction of the larger capacities and higher speeds.

Losses in Turbo-Alternators

The total iron and copper losses in a large, high-speed turbo-alternator are in general no higher than in a corresponding capacity low-speed machine.

As far as the iron losses are concerned, no further comment need be made than that the magnetic flux densities in general are somewhat lower than in lower speed machines of the same frequency, and therefore the losses per unit volume of material are no larger.

The total armature copper losses in turbo-alternators, as a rule, are considerably smaller than in corresponding capacity machines of the moderate or low-speed types. This is due partly to the use of a smaller total number of conductors, and partly to a lower current density in the armature conductors. As brought out before, in a narrow core machine, a considerable portion of the buried copper heat may be conducted lengthwise of the conductor into the end winding, and there dissipated into the air. In the turbo-generator, with its much wider core and greater distance from the buried copper to the end windings, a smaller percentage of the buried copper heat will be conducted into the end windings. To partly compensate for this, it is usual to work the armature copper in the turbo-generators at a lower current density, and therefore at a relatively lower total copper loss. This is somewhat of a handicap in the economical design of the generator, as extra space is thus required for the armature winding. In some of the earlier machines, the armature conductors were made of solid copper bars of relatively large section, partly for stiffening or bracing the end windings, as will be referred to later. With these solid conductors there was a very considerable loss in the buried copper due to eddy currents. To compensate for this, the armature conductors were made very large in section, so that the current density, due to the work current alone, was very low compared with

practise in other types of machines. On account of the comparatively large section of armature conductors, the conduction of heat from the buried copper to the end windings was relatively large. In some of these earlier, large capacity machines, the nominal current density in the armature conductors was so low, and the section of conductors so great, that the total buried copper loss, due to the work current, could be carried from the buried part of the coils into the end windings with a comparatively small drop in temperature, so that, if there had been no eddy currents present, the buried copper would have shown less rise than the iron. Any considerable rise which occurred was thus chargeable to eddy currents in the buried conductors, rather than to the work current. While such construction was fairly effective for the purpose, yet it was decidedly uneconomical in design, as indicated before. In fact, with later proportions and methods of design, the safe outputs of some of the earlier machines could easily be 50 to 75 per cent greater, largely on account of elimination of eddy currents and improvement in methods of dissipating heat from the end windings. In many of the older machines, the ventilation of the end windings was not nearly as effective as in modern types, due principally to the form and arrangement of the end connectors. Usually air spaces were allowed between adjacent coils, although, in some instances, these were so small as to give but little benefit. Moreover, in many cases, the type of end winding employed rendered these air spaces between coils rather ineffective, unless special means were taken to deflect the air between the coils. With later constructions, the end windings lie more or less across the path of the ventilating air, and there are ample openings between the coils, so that a very considerable part of the ventilating air will actually pass between the coils of the end windings in such a way as to give the maximum possible ventilation. When it is considered that the total armature copper loss may be only 20 per cent of the total stator loss it will be seen that an excessive amount of air is not required when the end windings are properly arranged for most effective ventilation.

Much effort has been expended in eliminating or reducing the eddy current losses in the buried copper of large turbo-generators, as well as in other types of large capacity alternators. These eddy currents are due to two sources, namely, the alternating magnetic flux across the slots due to the armature ampere

turns per slot, and secondly, the magnetic fringing from the rotor pole face into the open armature slots. In some instances, tests have indicated that the local e.m.fs. set up in the armature conductors by the flux through the slot opening are very considerably greater than those due to the flux across the slot. Obviously, with partially closed slots, this fringing into the top of the slot should be practically absent.

The simplest remedy for the eddy currents set up by these local e.m.fs. is to subdivide the conductors into a number of wires or conductors in parallel, so arranged or connected that the local e.m.fs. oppose and to a great extent balance each other. This opposition may be obtained by special arrangement of the conductors in each individual slot, or parallel conductors in the two halves of a complete coil may be connected in opposition to each other. Some of these arrangements do not completely balance the opposing e.m.fs., but they include the resistance of the complete coil in the eddy current circuit, so that the eddy losses are not only very materially reduced, but they are distributed over the entire coil, including the end windings, which condition, in itself, represents a very material improvement.

Protection Against Fire

An important problem connected with the insulation of large turbo-generators is found in the fire risk, or danger of destruction of the end windings due to starting an arc at some point. On account of the tremendous ventilation in such machines, a fire, if once started, may quickly ruin the entire end winding. An extended investigation was made, with a view to providing an insulation which would not burn rapidly. Among other tests, the end windings were finished on the outside with an asbestos covering or tape. However, such tape requires some sort of sealing varnish, or material to fill its pores, to keep it from absorbing moisture or oil. The tests showed that if a fire was once started, combustion would be maintained by the gases liberated by the "gasification" of the varnishes and other material in the end windings, whether the coil was covered with asbestos or not. No covering which was tested appeared to be very effective. Although some outside covering might be found which would be slightly effective in preventing fire from starting so readily, yet, if once started, it appears that a fire can very easily maintain itself in such machines. Eventually, the conclusion was reached that the safest course would be to

provide suitable closing doors or valves in the air inlets to completely shut off the incoming air to the machine. In addition, suitable doors on the air outlets, where they can be applied, should also be helpful, by retaining the smoke and burnt gases inside the machine, which thus assist in smothering the flames. The use of fire extinguishers of the gaseous type will usually be rather ineffective, unless the incoming air and ventilation is practically cut off. For instance, with 60,000 cu. ft. (1698 cu. m.) of air per minute passing through a large machine, the addition of a little gas for extinguishing the fire would hardly make any impression. In one instance, in attempting to extinguish a fire, an effort was made to feed the gas in against the ventilating pressure of the fans. Obviously, this would not work, and then a hose was used in order to get enough pressure to counteract the fan action. Although the fire was extinguished, the resultant effect of fire and the high pressure water was that new insulation was required.

Regulation and Short-Cirguit Characteristics

It has been known for many years to designers, that alternating-current generators can give, at the instant of short circuit, a much greater current than that which they will give on continued short circuit. The first emphatic evidence of this, in the writer's experience, was in connection with the first Niagara generators in 1894. Upon short-circuiting one of these machines at full speed and normal voltage, the results indicated a current rush so great that it was apparent that it was limited only by the armature self-induction, and not by the so-called synchronous reactance. Later, after being put into actual commercial service, it was found necessary to brace the end windings on these machines. However, at that time, no suitable instrument, such as the oscillograph, was available for determining the conditions on short circuit, and the phenomena did not permit of much experimental investigation.

Similar evidence was found from time to time, as in the first Manhattan Elevated engine type generators, which bent their end windings out of shape on a dead short circuit. But the real possibilities for trouble in this matter did not develop until the large capacity turbo-generators came into use. In these machines, the armature ampere-turns per pole are so high, compared with moderate speed alternators, that the stresses due to the stray magnetic fields on short circuit are much greater

than the natural rigidity of the end windings will withstand. The manufacturer of such apparatus, without data of any quantitative value at hand, did not fully recognize the real weakness in the end windings until disaster overtook them. Even then it was a long and difficult undertaking to overcome the trouble. All kinds of designs of end supports and various arrangements of end windings were tried, with more or less success. But each new step in the increase in capacity opened up the problem again. It was soon noted that those armature windings which were made up of cable or small wires, suffered most on short circuit, and for a while there was a tendency on the part of some manufacturers to use heavy, solid conductors to give rigidity in the end windings. This was effective within certain limits, but was very expensive from the design standpoint, as, on account of eddy currents in the buried copper, it was necessary to work at a very low current density, which was not economical in winding space.

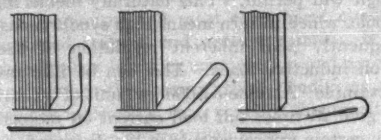


FIG. 20

In this country, the types of armature windings finally narrowed down to the open-slot construction, usually with an upper and lower coil per slot, with the end winding arranged in two layers, similar to d-c. armature windings, or the common induction motor primary windings. This turbo end winding was extended at various angles to the axis of the machine from almost parallel up to 90 deg., as shown in Fig. 20. The principal survivor of these types is one which extends at some angle between 30 and 60 deg. to the axis. There are several reasons for this—first, it allows a very substantial bracing to be applied to the end windings. Second, the stray fields around the end windings do not, to any extent, cut the adjacent solid parts, such as the end housings, stator and end-plates, etc. An angular position of approximately 45 deg. seems to be a good compromise on these points. Ample supports, as shown in Fig. 21, can be applied for bracing the windings against movement in any

direction. Such end windings are usually braced against metal supports attached to the stator end-plates. The coils are so clamped to the racks, and are so braced against each other that the windings will sustain a dead short circuit across the terminals, even in the largest capacity machines, without injury.

On some recent large turbo-generators, the end windings have been further strengthened by double metal racks between the two layers of windings, so arranged as to key these two layers securely to one another at certain points. Moulded mica troughs are placed around the coils as an extra insulation from the metal racks. By this keying of the two layers to one another, the winding as a whole is stiffened, quite irrespective of any other clamping arrangement. In fact, this is practically equivalent to putting the end windings in rigidly held slots, thus approaching the conditions which obtain in the buried part of the coil.

In order to limit the momentary short-circuit current, the armature reactance is now usually made as large as the condition of the design will permit. This naturally means high ampere-turns per pole, which in turn means high synchronous reactance, and consequently poor inherent regulation of the machine, especially on inductive loads. This can be illustrated by the following example: Assume a 5000-kw. unit of an earlier design, which can give 25 times full load current on momentary short circuit. By certain improvements in the design of the armature coils, such as the use of deeper slots, better subdivision of the copper to eliminate eddy currents, improved ventilation and conduction of heat, etc., the capacity of the machine is assumed to be increased to 10,000 kv-a., the number of armature turns remaining the same as before. It is evident that when short-circuited, the revised machine will give the same total current as on the former rating, which, however, is only 12½ times the rated current on the new capacity basis. Obviously, the end winding stresses are no greater than before, although the nominal capacity has been doubled, and if it were possible to brace the end windings satisfactorily with the former rating, the same bracing should be effective on the new rating. This illustrates, roughly, what is taking place in later designs, although the steps in the change may not be just those mentioned. Again, in the above example, it is obvious that, with the new rating, the inherent regulation at full load is the same as at 100 per cent overload on the old rating, which means that it is relatively poor. Another way to express this is, that the old rating might

give $2\frac{1}{2}$ times full load current on steady short circuit, while the new rating gives $1\frac{1}{4}$ times.

This condition of poorer regulation is inherent in the newer practise, but is apparently acceptable to the users of such apparatus, for a variety of reasons which do not come within the province of this paper.

Conclusion

The foregoing covers, in a general way, many of the problems encountered in large turbo-generators, and defines the situation as it stands at present.

It may be suggested, in connection with the temperature problem, that the high temperatures obtained are due to forcing the construction too far; but, in answer, it may be stated that it is forced no further in this feature than in many others. The whole design has been carried far beyond the most economical construction, from the generator standpoint alone. In fact, the whole machine is more or less a compromise between desirable conditions as a generator, and most economical conditions as part of a combined turbine and generator unit. It may be added that the ultimate limits in construction and capacity will be obtained only when the steam turbine conditions are satisfied, and there are indications that possibly this result is being approached now with the present high speeds.

There is one small consolation in all the confusion of development which has attended the turbo-generator work, in the few years it has been with us, namely, the question of choice of speed has been practically eliminated. For 25 cycles, there remains only one speed, namely 1500 revolutions, with two poles, from the smallest unit up to 25,000 kv-a. as a possible upper limit. For 60 cycles, up to 5000 kv-a., two-pole machines at 3600 revolutions are being furnished, while from this capacity up to 20,000 kv-a. four poles may be used.

It will be evident to any reader of this paper that the designers of large turbo-alternators have had a strenuous time during the past few years—very much more so than is indicated herein, for their successes rather than their failures have been discussed. In fact, much of the time they have been working ahead of their data and experience. In presenting this situation from the design point of view, it is hoped that a better and clearer understanding of the turbo-generator problem will be obtained by all who are interested in such apparatus.

DISCUSSION ON "HIGH-SPEED TURBO-ALTERNATORS—DESIGNS AND LIMITATIONS" (LAMME), NEW YORK, JANUARY 10, 1913.

Henry G. Reist: The author has treated this subject so fully that it leaves even those of us who have spent a good part of our lives on this work very little to add. He has weighed the different methods of construction so carefully, accurately and fairly that there is very little room for controversy, so what I have to say will be very brief and a part of it, at any rate, will be in the way of a slight further explanation of some of the methods of construction. The author limits the size of a two-pole machine of 3600 rev. per min. with a through shaft to about 600 kv-a. That is probably near the limit, if a solid shaft is used; but by the use of a flexible shaft, that is, a shaft which allows the rotor to run above the critical speed, the limits of output may be very materially increased. This is similar to the operation of the de Laval turbine, which in starting runs through a preliminary stage where it is not quite as steady as afterward, and then gets down to a perfectly quiet state. This construction does not require so large a shaft as if the machine were operated below the critical speed, and it is possible considerably to increase the limit of size. There are today a great many machines running, constructed on this plan, of from 1000 to 2000 kw. in capacity, at 3600 rev. per min.

The virtue of radial slots in rotors is well brought out in the paper. As the author points out, the stresses in the steel part of the rotor are all in tension, because the parts are radial, and there is no bending stress in the teeth; the radial slot design also allows the copper to be placed with the broad side against the next turn, so that no stresses come on the edges or corners of the copper. This is particularly advantageous where the ends of the coils are carried by a steel end ring. By having the ends of the coils radial, there is no side strain and comparatively little blocking is required to hold the coils securely in place.

Another point I might mention is that while a high grade of steel is used for making the weldless rings for supporting the windings, there does not yet seem to be any opportunity of making use of the higher grades of steel available, for the reason that the modulus of elasticity of the various grades of steel is about the same, and with a given stress in the ring the elongation will be approximately the same, whatever grade of steel is used. In order to avoid the ring loosening at high speed due to elongating, it should be placed on the rotor with a stress equal to, or greater than, that to which it will be subject while it is running. This is usually accomplished by heating the ring and shrinking it on. To enlarge it to the diameter it will have while in operation, requires heating to a temperature likely to injure the insulation while placing it into position. For this reason it is not desirable to go to the extreme in the stress which might be carried on these parts with the materials at hand.

As the author points out, one of the big problems in connection with the construction of turbo-generators is ventilation, and this is generally accomplished by subdividing the parts, and getting the air to move as rapidly over as large a surface of as many of the parts as possible. I agree with the author that it is really surprising what good results are obtained in this way.

The static discharge on coils is a trouble that is more prevalent than we generally appreciate—this corona appears at much lower potentials than we ordinarily suppose, with thick as well as with thin insulation. But, fortunately, it usually does not do much damage, for the process of oxidation is so slow that it extends over a very long time. As far as my experience goes, I do not recall any machine that was badly affected, that gave serious trouble, in a period of, say, less than six to ten years—and this with high-potential coils, 12,000 and 13,000 volts, and in some cases with fabric and varnish insulation. Probably if the coils were hot, the injury from this source would be very rapidly increased, since the corona produces an active form of oxygen which attacks the insulation chemically, and we know that chemical action is much more active when parts are heated than when they are cool.

Mica insulation, as it is made up for use for electrical purposes, is a composite material. It is built up of paper, usually, and a varnish, generally shellac, and mica. A good part of the thickness of the insulation consists of other material than mica, in many cases as much as 50 per cent. These other materials, as we use them at present, are similar in behavior to cotton cloth or varnish. That is, they do not resist high temperature and they will char. So that even a mica insulation, as built up, will have parts of it, that is, the interstices between the pieces of mica, char in subjecting it to high temperature, and we may expect that the corona will, even with mica coils (since they have the other combined materials in them) attack the mica insulation very much more rapidly if it is hot than if cool, because the other insulations will char. I think that some time we shall overcome this, because we shall probably obtain a varnish, perhaps a synthetic varnish, or wax, or gum, that will not be affected by the temperature at which our ordinary organic materials char. Then probably it will be advisable to go to higher temperatures, but until that time arrives I believe it is well to confine our heating, so far as possible, to points below 100 deg. cent.

In conclusion, I want to say just one word in regard to regulation, and that is, there does not seem to be any great advantage in good inherent regulation. I think I may say that this applies to almost all classes of alternating-current generators, because the best regulation that we can produce in any machine will not be good enough for commercial use in lighting, so that it is desirable to maintain constant potential either by hand or automatic regulation; the latter, of course, being ordinarily much better.

Now, if we have to regulate, we might just as well have poor inherent regulation of the generator, to obtain the various advantages, such as lower cost, higher efficiency, and particularly on the machines that we are discussing, much better protection against injury from short-circuit, so that we should practically eliminate the idea that we care about any special degree of regulation in this class of machine.

R. B. Williamson: As Mr. Lamme has pointed out, the design of a turbo-alternator is essentially an abnormal one from the electrical point of view, and the high speed combined with large output is a necessity imposed by the steam end of the unit. It is generally recognized that for a given output there is a certain speed at or near which the most economical design is obtained. Such conditions are frequently approached in water-wheel generators of large output. In turbo-generators the speeds are far beyond the point best suited to economical design and these excessive speeds are indirectly responsible for the difficulties encountered in the way of heating, ventilation, etc.

The coils in the radial slot type of rotor do not interfere with the shaft in either the two-pole or four-pole machines. So far as the coils are concerned, there is nothing to prevent the use of a through shaft, whereas in the two-pole parallel slot type a through shaft cannot be used unless some of the copper space on each side of the rotor is sacrificed (see Fig. 10 of the paper). Bolted-on stub-shafts therefore have a special advantage in this type of rotor. However, the possibilities of the radial slot rotor with a through shaft lie much beyond the limits stated on the second page of the paper. In the case of 3600-rev. per min., two-pole machines, generators of 1250 kv-a. output with through shaft have been built and successfully operated.

In large 25-cycle two-pole machines, a generator of 12,000 kv-a. output having a through shaft has recently been built and tested. A number of 60-cycle 1800-rev. per min. generators ranging from 5000 to 10,000 kv-a. have been built with through shafts and are in successful operation. Of course these machines operate above their critical speed, and it has been found that such rotors are easier to balance and, if anything, run more smoothly than rotors of similar design that operate below their critical speed.

As regards peripheral speeds, these are abnormally high at best, and the lower they can be kept without interfering with the design in other respects, the better will be the result. In the past, peripheral speeds have been pushed higher than necessary in some machines, and better results have been obtained by improving the ventilation and dropping back to smaller diameters and greater axial length. A marked reduction in windage loss with corresponding increased efficiency has thus been obtained.

As Mr. Lamme has clearly pointed out, the problem of ventilation is by no means an easy one, since the volume of air to be handled is so large and the space in which the heat is liberated

is so limited. So far as the rotor is concerned, the statement on page 13 regarding heat dissipation from the rotor surface is fully borne out by numerous tests. If the rotor winding is designed so that the heat can readily pass from the copper to the iron and thence to the outer surface, it can be removed by the scrubbing action of the air, which is very effective at these high peripheral speeds. Air ducts in the rotor, particularly radial ducts, are of doubtful advantage. They are usually much restricted at the roots of the rotor teeth and as some oil vapor always gets into a machine sooner or later, the dirt sticks in these small openings and shuts them off. The duct thus becomes a dead air space, which is worse than the solid metal so far as getting rid of heat is concerned, although when the machine is new it may be fairly effective. The loss in the rotor is not large, and if an ample supply of air is provided at the surface the scrubbing action will remove the heat, and the ducts are not necessary so far as the rotor itself is concerned.

The disadvantages of the circumferential method of ventilation mentioned near the bottom of page 10 have been entirely overcome by providing a sufficient number of multiple paths for the air currents in the stator. This shortens the paths and decreases the amount of air to be passed through any one section back of the teeth, thus reducing the velocities in the ducts. The plan shown in Fig. 14, which may be termed a two-path scheme, was satisfactory for machines of moderate output, and by carrying Fig. 16 still further and making say a 6-, 8- or even 12-path arrangement, very even and effective cooling is obtained, which enables long machines to be built which will be well ventilated at the central part. In this plan there is practically no interference of air currents, particularly when the rotor is made without ducts, and as the air blows radially inwards at several points against the surface of the rotor, the latter is well cooled.

In some cases the use of a separate blower may be desirable for large units, but by careful design a fairly good efficiency can be obtained in turbo fans, and it is a question if much is to be gained on the score of efficiency, especially when it is considered that separate blowers would have to be driven by a separate motor or engine, whereas the turbo fan derives its power directly from the turbine spindle. Moreover, the large air ducts and piping system required for separate blowers might prove objectionable in some cases.

It is pleasing to see the importance of air filters or air washers emphasized. Cloth air filters have been installed to some extent in the past, but they have often been worse than useless, as they have had insufficient area of cloth and the filters have soon become very dirty and clogged up and shut out the supply of air from the machine. A filter of this kind must have a very large area and consequently low air velocity. By arranging the cloth in zigzag fashion on suitable frames, an efficient filter can

be put into small space and built up in connection with the turbine foundation so as to form a very compact arrangement. A large filter made in this way has been in operation for a year and a half, and has such large area that it has not required cleaning during this time. In this installation there are two filters, each handling between 30,000 and 40,000 cu. ft. per min.

The matter of insulation is closely connected with the internal temperatures attained in the coils. Unquestionably most of the breakdowns in the stators of turbo-alternators have been between turns rather than to ground, and mica insulation between turns is desirable. Mica should also be used liberally in the slot portion of the coil, but, unless the machine is operated at temperatures in excess of 90 deg. cent., there is no objection to using varnished fabric in combination with the mica to give the necessary insulation in case the mica wrapper should become accidentally cracked.

The trouble due to static discharge perforating the outer layers of insulation next the iron is not peculiar to turbo-generators. The same effect has been noted on coils from a 6600-volt engine-type generator. In this case the outer wrapper or trough of fishpaper put on the coil for mechanical protection was literally riddled with pin-holes, while the varnished cloth insulation immediately underneath was in perfect condition, as was also the mica wrapper next to the copper. In a paper read in 1911 before the British Institution of Electrical Engineers by Mr. F. P. Fleming and Mr. R. Johnson, this effect is described and shown to be due to the fact that in a composite insulation of materials having different specific inductive capacities, it is possible to have a condition where the potential gradient across part of the insulation may exceed its disruptive strength, therefore perforating this part without affecting the rest of the insulation. It was also shown that this perforation might be caused by the double-voltage puncture test usually applied to machines.

So far as losses in turbo-generators are concerned, they are, with the exception of the windage loss, no higher than in other generators, and in some cases they are less. With a well-distributed rotor winding and with moderate peripheral speed, the core loss, assuming equal working densities, will be a lower percentage than in salient pole alternators. The stator and rotor copper losses will also be smaller, while the stray loss will be higher, the latter being due partly to the enclosed construction which allows stray flux to get into parts that are unlaminated.

Philip Torchio: I am asked to make some remarks from the standpoint of the user, and I may state that this is a point of view that sometimes escapes the designer. For instance, on page 6 Mr. Lamme says: "To avoid magnetic shunting of the field flux, this driving head must be made of non-magnetic material, usually of some high grade bronze...this makes a good strong construction, but is necessarily rather expensive,

due to the bronze driving heads. As these cost but little more for a long rotor than for a short one, the construction therefore tends toward relatively long, small diameter cores in order to lessen the relative dimensions of the bronze heads." That makes the machine longer, it may be one foot or three feet longer, and consequently the engine room one foot or three feet longer. It saves a few dollars on the bronze heads and necessitates our spending a few thousand in having a larger station. In many cases, space requirements are very important to us, and oftentimes it means that we have to sacrifice many thousand kilowatts simply for the reason that a larger machine cannot be put in a certain space because it is four or five feet too long.

As to the question of having outside blowers for ventilation, one of our allied companies is about to install some of these machines that Mr. Lamme has mentioned, and we were satisfied, because of the reasons given by Mr. Lamme and his associates, that outside blowers would be satisfactory; to facilitate their operation we have provided means through which, when the machine field switch is closed, the blower will be started automatically by a motor fed from some proper supply. I do not think that the cost or the efficiency of the system will be materially different; if anything, it will be a little better than having the blowers and the ventilating apparatus in the rotor itself, as Mr. Lamme states. If by adopting outside blowers you can reduce the size of the machine, I would emphasize to the manufacturers the desirability of doing that for large units.

At the bottom of page 24, Mr. Lamme states: "Of such machines it may be said that the manufacturer, with his guarantee of 40 deg. cent. by thermometer, actually builds for temperatures of from 70 to 90 deg. cent. in some parts of the machine, for he expects to find fairly high temperatures in some cases with exploring devices." I do not like that statement. We have been trying and failed to get the manufacturer to put exploring coils in the windings of the machine so that we could read them while we are operating the machine and see where the temperature goes. Now, if the safety of the insulation is limited within ranges below 100 deg. cent., and the room temperature may be 40 deg. or more, one cannot exceed 50 deg. maximum at any one point; it would not be safe at the present time to do it. In fact, if we do not have more troubles it must be that we do not carry the overloads or obtain the output that we should get from the machines, but which we may require at any moment.

The author says on page 25: "It also shows the absurdity of classifying a piece of apparatus as *good* or *bad*, respectively, according to whether it tests possibly one or two degrees below or above a specified thermometer guarantee." If I have a contract to pay $1,000, and give $900, the $900 may be perfectly good, but I will be short $100 of the amount which I must pay. The user has been buying in accordance with the thermometer readings, incorporated in the printed specifications of manufacturers. The standard should evidently be changed.

I am very much interested in the subject of the mica insulation, and I was a little disturbed by the previous speakers and Mr. Reist, particularly, who suggested that there may come another type of insulation to try upon us, as a better substitute for mica. My experience with mica insulation is too limited now to have any definite report to make, though the reason given by Mr. Lamme, that mica, being an inorganic substance, is not attacked by the oxygen, seems plausible. It is of general importance to know how to screen or to avoid ozonizing. I have had some experience in this matter, having had rather serious troubles on braided cable laid on imperfect ground. We found, for instance, that rubber insulation, which is more easily affected by chemical action, would stand the least, and we substituted paper or fabric, although I think it is undesirable—I do not speak of the interior of the machine, but the outside— to use a braided cable without a definite ground around it, like a lead sheath, because ozonizing is likely to take place at any time and under uncertain conditions

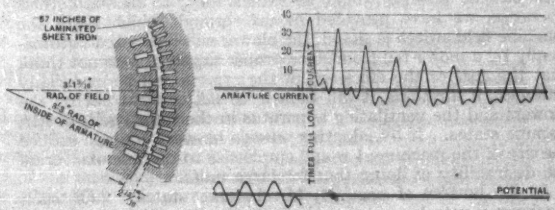


FIG. 8

over which one has no control, and by so doing one jeopardizes the protection of the apparatus. If the mica acts as a perfect screen, it might help in the cable manufacture and possibly in taping cable ends and splices.

I present seven illustrations giving a photographic reproduction of the very rapid deterioration of rubber produced by ozonization at moderately high voltage stresses upon the dielectric, having air insulation in series.

The experiment was made upon a sample of three-conductor cable with 5/32-in. (3.97-mm.) rubber insulation around each conductor. Ends were opened out about four inches between centers, leaving an air space between each conductor varying from zero at the apex to about 4 in. (102 mm.) at the ends. Voltage was applied between two conductors only. Fig. 1 shows conditions before voltage was applied, and Figs. 2 to 7 show successive stages after voltage was applied 40, 50, 60 and 70 minutes. Smaller cracks appeared after 20 and 30 minutes, but could not be photographed. Breakdown occurred after

FIG. 1—BEFORE TEST TORCHIO]

FIG. 2—18,000 VOLTS FOR 40 MINUTES [TORCHIO]

FIG. 3—18,000 VOLTS FOR 50 MINUTES [TORCHIO

FIG. 4—18,000 VOLTS FOR 60 MINUTES] [TORCHIO]

[TORCHIO]

FIG. 5—18,000 VOLTS FOR 70 MINUTES

[TORCHIO]

FIG. 6—PUNCTURED AFTER 70 MIN. 30 SEC. AT 18,000 VOLTS

[TORCHIO]

FIG. 7—CONDUCTORS SPREAD TO SHOW FAULT

70 min. 30 sec. It was shown that the rubber deteriorated at a point where there was about 0.4 in. (10.16 mm.) of air between the rubber surfaces, extending in each direction to points including 0.25 in. (6.35 mm.) and 0.5 in. (12.7 mm.) of air.

Similar results occur at considerably lower voltages, as low as 4000 volts, at correspondingly longer periods of electrification, when braided cables are not properly supported by insulators, but are laid on imperfect or intermittently imperfect insulators, like ducts, concrete, etc. Under the latter circumstances, which one should always try to avoid, the usual remedy, whenever the induced sheath currents are not too great, is to cover the cables with lead sheath, in which case the metallic sheath completely protects against ozonization.

I would like to ask Mr. Lamme if a similar solution might not be possible for high-voltage armature windings, making them metal-covered, so as to use fabric insulation while positively eliminating the trouble of ozonization affecting it, and at the

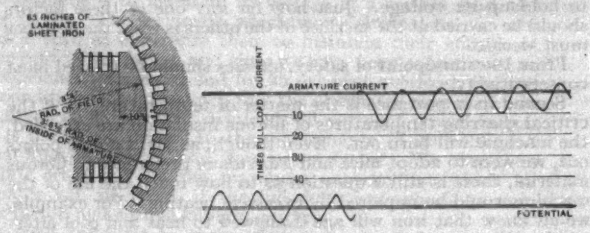


FIG. 9

same time improving dissipation of heat from the windings through the metallic sheath.

As to regulation of machines, designers might like to have definite information of what the results of radial slots and parallel slots would be. Figs. 8 and 9 refer to two 25-cycle, 8000-kw., 750-rev. per min. turbo-generators. Fig. 8 shows a radial slot machine with a distance between the armature and the field copper of 2 13/16 in. (71.4 mm.), and its corresponding oscillogram under short-circuit, indicating a maximum current 38 times the full-load current of the machine. With the parallel slot machine, of the same size, same frequency, same speed, but the distance between the copper of the armature and field 10¾ in. (273 mm.), the maximum current is about 14 times the full-load current of the machine. The short circuit took place at a voltage a little higher than zero; if it had been zero the current might have been a little higher, 15 or 16 times. These results show a great difference in the reactance of the two machines, due to the difference in the construction of the field.

C. J. Fechheimer: With few exceptions the limitations imposed by the rotor of the turbo prevent our reducing the size of the machine. In designing a turbo-alternator we first proportion the rotor and then place (on paper) the stator around it; whereas in designing low-speed alternators, we usually design the stator and then place a suitable rotor within it. It is of course essential to choose between the possible types of construction.

The limitations appearing in the rotor are:

(1) Stresses. (2) Temperature. (3) Cost. (4) Regulation. (5) Ability to maintain voltage.

A good design is necessarily a good compromise between these five factors.

Modifying any one of these factors will usually affect the remaining four. For example, we can, by increasing the stresses, reduce the cost of machine, lower the temperatures and possibly cause the machine to give better regulation and enable it better to hold up its voltage. Just how far any one of these factors should be carried at the sacrifice of the others is what the designer must decide.

From the standpoint of safety, stresses should be treated most conservatively.

Second in importance is the matter of temperature, for if the critical charring temperatures of fibrous insulation are exceeded, the machine will burn out. Even though, as Mr. Lamme points out, we were to adopt mica and asbestos in preference to fibrous material, there is still a question as to how much the life of the machine would be impaired by excessive heating. For example, we all know that iron will age if allowed to heat and cool alternately (this operation being repeated numerous times), the effect being that the efficiency would be reduced and the machine would heat still more. Furthermore, as stated by Mr. Lamme, it is advisable to fill the pores of asbestos material with inflammable varnish which, if subjected to excessive temperatures, will deteriorate with most undesirable effects.

We cannot afford, in commercial designs, to ignore the cost of the machine; and while for certain ratings we are so limited as to have very little choice, for the majority of conditions we have a larger selection, and therefore can materially affect the cost by wise or unwise proportions. In this connection it is essential for the designer to use as much foresight as is possible, for he must usually so proportion alternators that the principal parts can be used frequently in future machines without great modifications in patterns or dies.

Whereas regulation was considered to be of considerable importance about eight years ago, when machines were of smaller capacity than at present, we are feeling more and more that regulation, especially in large generators, can easily be sacrificed to gain in other respects. However, we must always bear in mind that even though we employ good regulators to main

tain constant voltage on one of the phases, there is a probability of having the voltages badly unbalanced if the load be different in magnitude or power factor on the various phases. This will be more especially the case if the inherent regulation of the alternator be coarse.

Mr. Lamme implies on page 36 that in some cases the rating of the alternator can be doubled, provided we can keep the stator cool enough, and have $1\frac{1}{4}$ instead of $2\frac{1}{2}$ times normal short-circuit current. We must remember that if we keep the number of turns in the stator the same, and increase the rating, the effective drop in the stator increases in proportion to the current, so that if the generator just maintains voltage for a given excitation at a certain power factor at the low rating, it would not be able to maintain its voltage at the higher rating, other conditions being the same. Hence, it may be essential to use more turns in the stator for the higher rating, and this will increase the drop still more. We can go so far that an increase in capacity for a given number of rotor ampere-turns will be impossible if the machine is to maintain its voltage at a certain load and power factor. The service to which many alternators are subjected is such as to require them to maintain their voltage at 80 per cent power factor, and since we have been accustomed to rate machines for normal and for 25 per cent overload, the full field conditions should be such that the alternator may maintain its voltage at 25 per cent overload, 80 per cent power factor. This is nearly equivalent to the maintenance of its voltage at normal kilovolt-ampere load, zero power factor. We may then calculate what will be the maximum capacity for which an alternator can be rated, if the full field corresponds to zero power factor, and normal kilovolt-amperes.

We shall endeavor to show what the maximum output is, using the following symbols to indicate the various quantities:

$A\,T$ = full field ampere-turns.
a = number of active conductors per slot.
E_i = internal voltage.
E_e = external voltage.
I = current.
n = number of phases.
P = kilovolt-ampere output.
p = number of poles.
R = reluctance of magnetic circuit.
S = number of slots per pole, per phase.
$\Sigma\,\lambda$ = equivalent of stator leakage paths.
ϕ = magnetic flux per pole.
X = stator leakage reactance per phase.
$\sim$ = frequency.

The internal voltage, if a sine wave be assumed, neglecting the pitch and distribution factors, is

$$E_i = 2.22\,\phi \sim S\,a\,p \times 10^{-8}$$

The flux per pole is

$$\phi = \frac{(A\,T) - \dfrac{a\,S\,n\,I}{2\sqrt{2}}}{R},$$

where the second term in the numerator is the armature reaction per pole. R includes $\frac{4\pi}{10}$ (3.19 for inch system).

At zero power factor the armature resistance drop is negligible, and we may therefore write

$$E_e = E_t - I\,X$$

And for simplicity,

$$X = 2\,\pi \sim a^2\,S\,p\,(\Sigma\,\lambda) \times 10^{-8}$$

The kilovolt-ampere output is

$$P = n\,E_e\,I$$

Combining the above equations, we obtain

$$P = n\,I\left\{\frac{2.22}{R}\left[A\,T - \frac{a\,S\,n\,I}{2\sqrt{2}}\right] \sim S\,a\,p \times 10^{-8} - 2\,\pi \sim a^2\,S\,p\,I\,\Sigma\,\lambda \times 10^{-8}\right\}$$

Assume constant magnetic reluctance (true with straight-line saturation curve) and that output is increased by augmenting number of conductors (equivalent to increasing electromotive force; same results are obtained by considering number of conductors constant and current variable). To determine maximum output obtainable with given number of field ampere-turns, we differentiate the above equation with respect to a, and equate to zero, and obtain after simplifying:

$$a = \frac{\sqrt{2}\,(A\,T)}{n\,I\,S + 8\,R\,I\,\Sigma\,\lambda}\,*$$

The first term in the denominator in this expression is dependent upon armature reaction; the second term upon armature leakage fields (reactance).

*The form of the equation, before solving for a, was of first degree; hence only one solution was possible. The physical interpretation of this is that if the number of conductors is indefinitely *decreased*, an output of zero is approached; whereas, if the number of conductors is *increased* without limit, the reactance, being proportional to square of conductors, causes a greater drop in the armature than the value of terminal voltage.

In most turbo-alternators the number of field ampere-turns required to compensate for the drop in voltage due to armature leakage fields is small compared with the ampere-turns needed to compensate for armature reaction (counter magnetomotive force at zero power factor). To assist toward obtaining a simple physical interpretation of the above equation, we shall disregard for the moment the second term in the denominator, and then find

$$A\,T = \frac{a\,S\,n\,I}{\sqrt{2}}$$

That is, the full field ampere-turns are just double the armature reaction $\left(\frac{a\,S\,n\,I}{2\,\sqrt{2}}\right)$. This condition obtains if armature resistance and reactance are negligible: that reluctance of magnetic circuit is constant, and that generator just requires $A\,T$ ampere-turns on the field to maintain normal voltage, with normal kilovolt-ampere output at zero power factor.

To further interpret our results, we see that with the straight-line saturation curve assumed, we shall have 100 per cent regulation at zero power factor, and that normal current will flow if the alternator be gradually short-circuited with the excitation required for no-load normal voltage. In this latter case the ampere-turns in the field are just one-half the full field ampere-turns.

If we take into consideration the saturation of the magnetic circuit (variable reluctance), and the effect of local armature impedance, we see at once that, due to the former, the regulation at zero factor will be somewhat finer than 100 per cent; and the ampere-turns in the stator, for maximum kilovolt-amperes, will be somewhat less than one-half of the full field ampere-turns. In other words, somewhat more than normal current will flow when short-circuited with no-load field. The result which Mr. Lamme speaks of ("$1\frac{1}{4}$ times short-circuit current") is about the condition for maximum output.

The question arises: would it not be possible to employ a smaller air gap and secure a larger output? This undoubtedly could be done if the steel in the magnetic circuit did not become prohibitively saturated. If the air gap and parts of the magnetic circuit were reduced to have zero reluctance, we should only require sufficient ampere-turns to overcome armature reaction and impedance, and the regulation would be infinite. To secure maximum kilovolt-amperes with diminished air gap, we should most advantageously use a larger value of flux, provided the iron did not saturate too highly, and we would still have the relation that full field ampere-turns would be twice the armature ampere-turns, and normal current would flow on short-circuit with no-load excitation were the reactance and resistance of negligible

value. The rating would then be increased in proportion to the increase in flux.

Mr. Lamme speaks of air velocities as high as 10,000 ft. (3048 m.) per minute. When we remember that losses in air are proportional to the cube of the velocity, we shall readily appreciate that the losses with such velocity may be excessive. I ask Mr. Lamme how such velocities are measured in the machine; whether he attempted to measure air velocities directly in any parts not easily accessible.

William LeRoy Emmet: I am glad this paper has been written, because it gives everyone who reads it a comprehensive idea of all the work which has had to be done in the design of these high-speed alternators and the limitations of these designs. We know from experience that the difficulties of designing are too often overlooked by engineers who desire to purchase or install alternators, but all these limitations should be very carefully studied and considered, and the manufacturer should not be forced into conditions which are undesirable or entail difficulty. There is one thing which I think should be considered in connection with the design of large alternators, and that is, that the value of the product which they handle is enormous, in proportion to the cost of the machinery, and consequently we can afford to use only the best, and even if the machine costs a great deal more, if it is better or simpler or more reliable, it ought to be used. We should not, in other words, incur risk or inefficiency or difficulty of any kind on the score of cost in apparatus of this type. A very simple glance at the figures involved in the fuel consumption of such machines in a year's service will show that to be true.

As in other things, purchasers should not limit manufacturers unless that limitation is in the direction of value, and I am very sympathetic with Mr. Lamme in what he has said about temperature, that it would be highly desirable if we could build apparatus for higher temperatures, and if we could do so we could make it more efficient and make many improvements, provided the temperature could be run higher. The question has been in my mind as to what temperatures we should use in large apparatus. I have worked with a view to recommending to our customers what I believed to be the very best engineering solution of the problem, whether we get the job or not, in these cases, and I think that in so doing it is a nice question as to what type of insulation we should use. Insulation of all types which we have is very imperfect, and if we could find some better means of insulating high-voltage machines we would be very much better off, but I am a little disposed to differ with Mr. Lamme's implications that we could use temperatures, safely, as high as 125 deg. cent. Mica, of course, is indestructible at such temperatures, but as Mr. Reist has said, a great deal of other material is used with mica, and this is not only subject to destruction by heat, but subject to a sort of destructive distillation which

causes fumes and other constituent parts of these substances to percolate through the insulation and seek out paths of discharge, and this destructive distillation of insulating materials is a very important cause, I think, of trouble. I have seen cases of burn-outs in mica-insulated machines of the most approved designs which rather clearly showed the danger in this direction, and with our best work in heat-proof insulation, I believe that we do not quite reach the state of safety that we do with cool machines. In some of these large machines the question of getting coolness means making the machine larger. That, of course, increases its cost, and also increases the mechanical difficulties—difficulties of shipment, difficulties of getting the forgings, difficulties incident to windage, which are very great at high velocities. However, with the best methods of cooling, it is astonishing what an amount of heat can be removed by virtue of the fact that rapidly moving air scours away the heat from the surfaces. We have worked very cautiously in the use of high temperatures. We are trying hard to build machines to run hot, but have not yet reached the point where we dare to do so.

Paul M. Lincoln: Perhaps the most significant feature about Mr. Lamme's paper is that about two-thirds of it is discussion of the closely related subjects of ventilation, temperature and insulation, and such things as inspection and cleaning of air and discussion of the mechanical details, make up the other third. That is a good indication of just how serious a problem the ventilating and cooling of a turbo-generator has become.

Another thing which this paper brings out plainly is that turbo-generators must be very efficient machines. All of the losses in the generators, of course, turn into heat, and the problem of carrying away that heat is the greatest one to be solved, and consequently it is almost essential to build turbine generators of comparatively high efficiencies.

There is one additional matter which has not been touched on, except slightly by Mr. Fechheimer, and that is the fact that the high velocities of the air which are necessary in order to carry off the heat from the restricted surface of the turbo-generators, may of themselves, if carried too far, generate undue heat. In fact, the windage losses in our turbo-generators are quite a large proportion of the total losses, and these windage losses come on account of the inherent difficulties in the problem so plainly set forth in Mr. Lamme's paper; that is, they come on account of the comparatively large amount of heat to be carried away from a restricted surface. If the air velocities are carried too high the method defeats its own object, because of the amount of heat that is put into stirring up the air.

I notice the expression which was used by Mr. Reist—"good inherent regulation," which he named as a bad thing. Now that is a nomenclature which is certainly unfortunate, because when we say "good inherent regulation" we mean one which is

objectionable. It seems to me we might find a little better term to describe the kind of regulation which we would say is not objectionable.

Referring to Mr. Williamson's discussion, he described, as I understood him, an air filter which ran for over a year and did not get dirty. I must say that I am unable to conceive of an air filter which takes the dirt out of the air without itself becoming dirty. If it does not become dirty, it seems to me self-evident that it is not a good air filter.

Mr. Williamson also stated one thing which deserves some further discussion, when he mentioned the fact that if we had an insulation which would carry the heat readily from iron to copper, or copper to iron, our difficulties would be largely overcome. Now, that is an impossibility. We cannot design an insulation which has a good heat conductivity. The heat resistance of the insulations which we have in turbo-generators is about 1000 to 3000 times that of copper, and it is not possible by any means we know of to get a heat conductivity very much better in any known insulations. We must put up with those thermal drops in the insulation. There is no way to avoid them.

Peter Junkersfeld: The most suitable voltage for a given generator is, of course, largely a question of the insulation material and other limitations of design that exist at that particular time. In Chicago we have installed two 20,000-kw. 25-cycle units in a new station within the last year in which the voltage was half the busbar voltage, stepping up through auto transformers, and in so doing securing the necessary reactance at the same time. On the other hand, more recently we have, with better insulating material available, ordered a unit of the same total maximum kw. output in which the generator voltage will be the same as the busbar voltage. That happened to be a 60-cycle machine in which the problem of securing sufficient reactance was not difficult.

I feel, however, on this whole matter of generator design, that there is one point that perhaps has not been given as much attention as it should have been given, and that is the arrangement and smoothness of the air passages. Mr. Lamme, in Figs. 15 and 17, gives diagrams showing how air passes through certain designs of machine, but air has a habit of not turning right-angle corners, and not always behaving the way you want it to; moreover, air, notwithstanding what Mr. Lincoln has said about the filtering of air, is always dirty to a greater or less extent, and I do not believe that is confined solely to Chicago air, either. Air filters are not only very expensive, but, so far as I know, they have never come quite up to expectations, and, further, they are difficult to build in any fireproof form, or even semi-fireproof form. The requirement should be to get along without air filters if it is possible to do so. Some installations are becoming so large that it will probably pay, in large installations, to put in air filters and make the best job we can,

but in small and moderate size stations I doubt if it will pay. The arrangement and smoothness of air passages should, therefore, be an important factor in selecting a generator design. I do not mean it should be the controlling feature, but when you have taken into account all the other limitations you should make a special effort to get a machine which is least likely to clog up with dirt.

That brings up another point. As soon as a machine begins to clog up with dirt, whether it occurs in one month, or six months, or twelve months, windings in the slots will necessarily become hotter, and for that reason temperature coils are very desirable in the machine, because they give an indication as to when the machine has reached, or is approaching, the absolute temperature for which it was designed. Notwithstanding the fact that temperature coils do not give absolutely accurate data, as pointed out by Mr. Lamme in his paper, they give the best and most positive indication you can have that it is time to go to the expense of taking down that machine and cleaning it thoroughly.

I am glad to hear both Mr. Lamme and Mr. Emmet speak of higher temperatures, and sincerely hope that their expectation may be realized, but before purchasers will agree to very much higher temperatures they naturally must feel reasonably certain that the machines will be at least as reliable as they are now.

The experience of the past ten years, as most of you have known, and as the author of the paper points out, has been a strenuous one and not at all times satisfactory. With the fibrous insulation 85 deg. cent. seems to be about the safe ultimate temperature. With the mica insulation it, of course, should be and probably will be very much higher. A slight difference in cost is not a serious thing with a very large machine, and while higher temperatures are very desirable we should not go to them if we are going to have a lesser factor of safety than we have at the present time with fiber insulation and only 85 deg. cent.; in other words there is still need for considerably more reliable generators than there are in existence today.

H. M. Hobart: There is one method of filtering, or, at any rate, cleaning air, which certainly would not involve any fire risk. The method to which I allude consists in washing it by passing it through sprays of water. It has the additional advantage of imparting to the air a certain amount of humidity and this is associated with a decrease in the initial temperature, which goes part way toward modifying the limitations imposed by the maximum temperature that the machine can endure. Five degrees decrease of temperature at the inlet is certainly well worth while. I am glad that the present trend of engineering opinion is in the direction of employing a central plant for the provision of the air. It permits not only of conditioning the air in the way I have mentioned but it also frees the designer from one set of considerations with which there is no need that he

should be embarrassed. Any one who has read Mr. Lamme's paper will have considerable respect for the task of designing an extra-high-speed turbo-alternator, and will be disposed to agree that, other things being equal, if you can relieve the machine of all other duties than that of turning out electricity, it is in the interests of obtaining the best result. Large modern stations often require a total amount of air of some 200,000 cu. ft. per min., or even more, and the provision of this large amount of air is in itself a fairly elaborate undertaking. It can be worked out much better by putting in a separate plant with motor-driven blowers. Mr. Lamme has reasoned out very clearly that if we are determined to have these high-speed machines we must put up with higher temperatures than would be associated with machines of less speed.

Mr. Lamme goes on to develop the point that with these extra-high temperatures, the point of weakness is not in the copper; there will not be any trouble there because of any heating of the copper itself; nor in the iron, but in the insulation. In these extra-high-speed machines it is necessary to have a considerable pressure between adjacent turns. The higher the speed the less the turns and the higher the pressure per turn, and thus the question is not simply that of the copper and iron, but also of the insulation between the turns, as well as of the main insulation between the copper and iron, which bound this hot copper and this hot iron. We must admit that insulation appropriate for use in the slots has not the heat-resisting character possessed by metallic materials. Nevertheless, very great progress has been made in the matter of developing insulation in recent years. For a long time questions relating to insulation were apt to be ignored. Designers would deal carefully with the copper part and with the iron part of the structure, but the insulation has usually been sadly neglected.

Now, however, a very great advance has been made, and we have arrived either, as Mr. Lamme is inclined to believe, at a stage where we can safely use these high temperatures (and personally I will say frankly I agree with him) or, even if he and I are a little too sanguine, we are at any rate just on the point of arriving there. Every few months records further progress in these directions, and personally I feel that we should consider the temperatures named in the paper as those which can safely be used, with ample regard for the customer's side of the case.

What does the customer want? He does not necessarily want a machine that will last twenty years. None of us have seen even *ten* years go by, without the machinery which was produced at the beginning of the ten years having become so inferior to machines which could be produced in accordance with up-to-date knowledge that it would pay to scrap that machinery. The factor of obsolescence is thus one of great importance. Is it really good engineering in figuring on depreciation in the case of electrical machinery of this kind to spread it over so long a

term as twenty years? My own opinion is that ten years will be a liberal provision. As has been stated by one or two of the speakers, these large high-speed machines are enormously expensive. The initial outlay for a 10,000-kw. turbo-generator may run into a matter of $100,000, and if that is spread over ten years, adding the capital charges, interest, allowance for insurance, taxes, etc., the total capital investment would probably average $200,000, or something like $20,000 a year. That is merely the line of argument; the precise values I have assigned have no special significance, though their order of magnitude is correct. $20,000 per annum seems a large figure, but it is small compared with the cost of the fuel for which that generating set is responsible per annum. I have not figured it out closely, but I believe that fuel consumption runs to something like $50,000 or $60,000 a year, as against $20,000, representing these capital costs of the turbo-generator. Then there is also the outlay for labor and attendance, etc. Therefore, anything that will conduce to decreasing the large fuel cost can quite properly be associated with a shorter life. It is for the purpose of decreasing the fuel cost that we resort to the very uttermost speed. You may say that having got that fuel cost away down, we want the machine to last a long time, but let me remind you that when ten years have elapsed that fuel cost will not represent the limits of economy to which we have attained. We will then be able to build machines for considerably lower fuel costs. But the point is that we want a good, sound machine, useful throughout its ten years' life. It should be a fine engineering product, on the basis that ten years is approximately the estimated life of the insulation. It is not undergoing deterioration throughout every hour of the ten years. It would be rare in central station practise for a 10,000-kw. machine to be in service more than 2500 hours out of the 8750 hours that make up the year. Let us take 25,000 hours as the aggregate time in service in ten years, and the problem is to provide insulation for a life of something like 25,000 hours' exposure to well on towards 125 deg. cent.

That is the problem engineers must consider in designing such machines, and they are rapidly getting where they can tackle it on that basis and provide the appropriate insulating material. This seems to me to be the correct proposition for cases where the insulation is the limiting feature. The fact is brought out in the paper that since the question of insulation is the one point which constitutes the limitation, we should devote our energies to that purpose and get the right stuff for it. The resources of modern engineering have never before failed us and are not going to fail us at this juncture, and if we determine upon this high temperature limit we shall learn to meet the new conditions imposed and meet them with safety. We should also follow up the related problem of getting a maximum amount of air through the machine. The more air we get through the machine the

lower the temperature, or, for constant temperature, the more air we get through, the larger output we can go to, and we may not be limited to a 6000-kv-a. turbo-generator for a speed of 3600 rev. per min., or to a 25,000-kv-a. generator for a speed of 1500 rev. per min. We may be able to go to higher outputs for these speeds. It is in these directions, the methods of cooling and the methods of designing insulations which will stand higher temperatures, that our efforts should be put forth, so far as the kind of machinery we are discussing is concerned, namely, extra-high-speed machinery for large outputs.

W. L. Waters: Mr. Lamme's paper is especially interesting at the present time when the design of the modern turbo-alternator appears to be settling within the well-defined limits which have been decided by the materials commercially available. As pointed out, the design centers around the field magnet—the limitations being more serious on this than on any other part of the unit. The parallel slot type of magnet as developed by Mr. B. G. Lamme, and the radial slot as developed by Mr. C. E. L. Brown, are the only two commercial possibilities at the present time for high-speed generators. The former is a much simpler manufacturing proposition and the insulation is subject to less severe operating conditions, but it suffers from the difficulty of obtaining suitable commercial material in the required form and of determining the actual distribution of stresses. These limitations have recently brought the radial slot type into prominence for large high-speed units; the question of reliable and commercial high-grade materials being solved by the adoption either of a solid rotor built up of rolled plates, or of a rotor in which loose teeth of laminated steel are dovetailed into a hollow forged cylindrical drum.

The design of the stationary armature is comparatively simple, except for the question of ventilation, which, as stated, frequently becomes quite a serious problem in the case of high-speed units of large capacity. The system of ventilation first worked out in Germany, which consists of axial ventilation of the armature, combined with a ventilated rotor, seems to offer the greatest possibilities for such units. But, as pointed out, complicated systems of ventilation are rarely successful, as the various currents of air always interfere with one another. The problem of ventilation is not only to force a certain quantity of air through the machine, but also to do it with as little expenditure of energy as possible. Most of the energy required to force the air is wasted in eddies and churning, and this wasted energy raises the temperature of the air, thus decreasing its cooling effect. I remember one case in which a generator provided with an inefficient blower absorbing 100 h.p. actually operated with a lower temperature rise when the fan was removed; and there are a number of turbo-generators on the market in which, when rotating without load or excitation, the temperature of the air is increased 15 deg., due to eddies and churning while passing through the machine.

The cooling system of most turbo-generators is undoubtedly inefficient, but personally, I doubt the accuracy of the very high local temperatures sometimes obtained from resistance coil or thermocouple measurements. It required ten years' experience of the manufacturers and a considerable amount of work by the Standards Committee before any reliability was obtainable in temperature measurements by thermometer, and I think it will be necessary to duplicate this work before any reliance can be placed on the usual resistance coil or thermocouple tests. Such measurements must at the present time be considered as laboratory tests requiring an observer experienced in the use of such methods, and are worse than useless in the hands of the average tester. The most reliable deductions are those drawn from examination of the condition of machines that have been in operation, and as Mr. Lamme has pointed out, these results emphasize the advisability of employing some high-temperature insulation such as mica in both the field magnets and armature of any generator subject to the severe operating conditions of the modern large high-speed turbo-alternator. Mica as an insulating material for electrical power machinery has been in disrepute for the past fifteen years on account of its poor mechanical properties, and it is only during the last few years that methods have been devised for using this material under conditions which do not allow it to be subjected to mechanical abuse either during the manufacturing processes or in practical operation. These developments in regard to the use of mica as an insulator have had an important influence on the development of the modern high-speed turbo-alternator of large capacity.

The point in Mr. Lamme's paper which probably affects operating engineers most is that it is clearly shown that the carefully worded specifications and elaborate detailed guarantees usually required, are not only of little value, but inadvisable, as tending to give a false idea of security. The selection of satisfactory materials, the limiting of stresses to safe values, the choice of insulating materials and the adoption of an adequate system of ventilation which will avoid the presence of dangerous temperatures in inaccessible parts of a machine, are all questions which can be passed upon only by an engineer who has had wide experience in the design, manufacture and operation of these units; and on such questions, the detailed guarantees usually specified have practically no application. Large high-speed units are coming into increasing use every year and it will be well for prospective purchasers to realize that they must necessarily depend on the ability and standing of the manufacturer when buying such units, rather than on some specification containing a number of more or less unimportant guarantees.

Comfort A. Adams: Mr. Lamme has made such a thorough job of the subject in hand that I will confine my discussion to a more quantitative treatment or explanation of a few of the points made in the paper.

First, consider the relation of armature copper and core losses as between engine-driven and turbine-driven alternators. For a given gap density and coil pitch, the volts per foot of active conductor will be proportional to the peripheral velocity, or the total length of active conductor inversely as the peripheral velocity. Thus if the current density in the copper is unchanged, the armature copper loss is inversely as the peripheral velocity. A change in the ratio of idle to active wire or in the coil pitch may modify this proportionality somewhat when applied to the total armature copper loss, but not seriously. Thus a jump from a peripheral velocity of 100 ft. per second in an engine-driven alternator to 400 ft. per second in a turbo-alternator means a reduction of armature copper loss to approximately one-fourth.

With the core loss it is quite different. For a given frequency and magnetic density, the pole pitch and therefore the depth of core back of slots is proportional to the peripheral velocity; thus any reduction of cylindrical core section is neutralized by the increased core depth; moreover, the ratio of outer core diameter to gap diameter is so much larger in the two-pole and four-pole machines that the core volume and thus the core losses are considerably greater for the same magnetic densities. The actual ratios are as follows: a two-pole machine has about 80 per cent more core volume and core loss than a 60-pole machine, other things being equal, a four-pole machine 40 per cent more, an eight-pole machine 20 per cent more, and so on. This increase of core loss back of the slots is, however, slightly neutralized by less tooth volume and tooth loss. Thus the ratio of core to copper loss is several times as great as in the engine-driven machine. This has an important bearing on the method of ventilation, as indicated in Mr. Lamme's paper.

A similar change in distribution takes place between the various elements of leakage reactance, the slot leakage decreasing as the length of active conductor decreases and the peripheral velocity increases, while the coil end reactance increases materially.

Coming now to the question of heating, it may be interesting to apply a simple calculation to a condition which is sufficiently near the facts in some cases to make the results significant and instructive. Consider a copper conductor completely heat-insulated laterally so that the heat generated therein must flow to the ends—to find the difference of temperature between the center and the ends.

Let l = embedded length of conductor in core (cm.).
a = current density in amperes per sq. cm.
ρ = resistivity of conductor in ohms per cm. per sq. cm.
$p' = a^2 \rho$ = watts per cubic cm. of conductor.
θ = thermal resistivity of conductor in deg. cent. per watt per cm. per sq. cm.
x = distance of any point from center of conductor.
$p' x$ = watts flow of heat through the conductor at x.

Then the difference in temperature between the ends of the element dx is

$$dT = a^2 \rho \theta x \, dx$$

and the difference of temperature between the center and end is

$$T = a^2 \rho \theta \int_0^{\frac{l}{2}} x \, dx = \frac{a^2 \rho \theta}{8} l^2 \qquad (1)$$

Taking $\rho = 2.20 \times 10^{-6}$ (at 90 deg. cent.) and $\theta = 0.29$,

$$T = 8 \left(\frac{a}{100}\right)^2 \left(\frac{l}{100}\right)^2 \qquad (2)$$

Table I gives values of T for various values of a and l

TABLE I

Amperes per sq. cm.	Amperes per sq. in.	Cir. mils per ampere	l			
			20 in. 50.8 cm.	40 in. 101.6 cm.	60 in. 152.4 cm.	80 in. 203.2cm.
150	970	1310	4.65 deg.	18.6 deg.	42 deg.	74.5 deg.
200	1290	985	8.3 deg.	33.2 deg.	75 deg.	133 deg.
250	1610	790	13.0 deg.	52 deg.	117 deg.	208 deg.
300	1940	655	18.6 deg.	74.4 deg.	168 deg.	297 deg.
400	2580	493	33.2 deg.	133 deg.	300 deg.	530 deg.

There is thus a pretty definite limit to the safe length of embedded conductor unless considerable heat escapes through the slot insulation, or, for a very long core it is pretty certain that most of the heat generated near the center of the embedded conductor must flow through the slot insulation.

In such a case the temperature difference between slot copper and core may be approximately determined as follows:

Let S = area of section of coil (or double coil in a two-layer winding) inside of coil- and slot-insulation. The perimeter of this section, or the cross-section (per unit of slot length) of the path through which the heat must flow, will be, for an average slot shape, $4.5 \sqrt{S}$.

Let f_s = copper space factor within the coil insulation.

Then the copper watts per cm. length of slot will be

$$p'_s = (S f_s a)^2 \rho \frac{1}{S f_s} = \rho S f_s a^2$$

Let θ = the thermal resistivity in deg. cent. per watt per cm. per sq. cm., and t = (cm.) thickness of insulation, iron to copper. Then the temperature difference between copper and iron will be

$$T = \frac{p_s'}{4.5\sqrt{S}}\,\theta\, t = \frac{\rho\,\theta\, f_s}{4.5}\, a^2 t\sqrt{S}$$

$$T = (\rho \times 10^6)\left(\frac{\theta}{10^3}\right)\left(\frac{a}{100}\right)^2 (10\,t)\sqrt{S}\, f_s \qquad (3)$$

Take $\rho \times 10^6 = 2.2$ (90 deg. cent.), $\frac{\theta}{10^3} = 0.7$, and $f_s = 0.8$ (large machine, bar-wound).

This value of θ is an average for the ordinary slot insulations. Then

$$T = 2.2 \times 0.7 \times 0.8\left(\frac{a}{100}\right)^2 (10\,t)\sqrt{S}$$

$$= 1.23\left(\frac{a}{100}\right)^2 (10\,t)\sqrt{S} \qquad (4)$$

or the temperature gradient in deg. cent. per mm. is

$$T_m = 1.23\left(\frac{a}{100}\right)^2 \sqrt{S} \qquad (5)$$

Values of T_m are given in Table II for various values of a and S.

TABLE II

Deg. cent. per mm. thickness of insulation.

Amperes per sq. cm.	S						
	0.25	0.50	0.75	1.00	1.50	2.00	2.5
	deg.	deg.	deg.	deg.	deg.	deg.	deg.
150	1.39	1.95	2.4	2.77	3.4	3.92	4.38
200	2.46	3.48	4.26	4.92	6.03	6.95	7.8
250	3.85	5.45	6.67	7.7	9.43	10.9	12.2
300	5.55	7.85	9.6	11.1	13		
400	9.84	13.9	17				

For wire-wound machines f_s will be less, but there may be a considerable temperature gradient between the center of the coil section and the inside of the coil insulation, so that equation (5) will give too small values if used to determine the maximum internal temperature of wire-wound machines, particularly where there are many turns of fine wire.

When considering the flow of heat from copper to iron, it is obviously desirable to know what happens in the iron itself.

Consider a large mass of laminations in which heat is being generated by core loss at the rate of p' watts per cu. cm.

Assume first that the heat flows only parallel to the laminations, and let l be the total depth of laminations. Then, from equation (1),

$$T = \frac{p'\theta}{8} l^2 \tag{6}$$

Take $\theta = 2.4$. Then $T = 0.3\, p' l^2$ (7)

Table III gives values of T for various values of p' and l.

TABLE III

p'	Watts per cu. in.	Watts per lb.	l					
			4 in. 10.2 cm.	8 in. 20.3 cm.	12 in. 30.5 cm.	16 in. 40.6 cm.	20 in. 50.8 cm.	30 in. 76 cm.
			deg.	deg.	deg.	deg.	deg.	deg.
0.01	0.164	0.58	0.31	1.25	2.8	5	7.7	11.2
0.02	0.328	1.16	0.62	2.50	5.6	10	15.5	22.3
0.03	0.492	1.74	0.94	3.75	8.4	15	23.2	34.0
0.04	0.656	2.33	1.24	5.00	11.2	20	31	44.7
0.05	0.82	2.92	1.55	6.25	14.00	25	37.7	56

This assumes that the two exposed edges are at the same temperature. If this is not the case, the temperature difference will be slightly less with respect to the hotter edge and greater with respect to the cooler edge or surface.

Next assume that the flow of heat in the core is entirely across the laminations. From Table III it is obvious that in the case of deep cores without transverse or axial ducts, the above assumption will approximately represent the facts, at least so far as the radially central part of the core is concerned.

For this case take $\theta = 30$. This varies considerably with the tightness of the laminations, and is frequently larger than the value here assumed.

Equation (6) thus becomes

$$T = 3.75\, p' l^2 \tag{7}$$

Table IV gives values of T for various values of p' and l.

TABLE IV

Watts per cu. cm. p'	l			
	2.0 in. 5.08 cm.	2.5 in. 6.34 cm.	3.0 in. 7.62 cm.	3.5 in. 8.9 cm.
0.01	0.97 deg.	1.5 deg.	2.17 deg.	3 deg.
0.02	1.94 deg.	3.0 deg.	4.35 deg.	6 deg.
0.03	2.9 deg.	4.5 deg.	6.52 deg.	9 deg.
0.04	3.88 deg.	6.0 deg.	8.7 deg.	12 deg.
0.05	4.85 deg.	7.5 deg.	10.9 deg.	15 deg.

These are merely suggestions of what may be done with simple calculations, the results of which, though somewhat crude, are very significant.

Mr. Lamme's paper illustrates what the writer has so often urged, the importance of careful analysis of each problem from the groundwork of fundamental principles, the habit of thinking rather than simply remembering, and particularly the habit of thinking *first* before being forced to do so by the failure of some plan or design.

Allan B. Field: Mr. Lamme's description of the general turbo situation carries us so easily through the history that we are apt to overlook the great difficulties that were encountered in connection with the early big machines, five or six years ago, the difficulties, for instance, in obtaining suitable large steel forgings and castings. Mr. Lamme and his associates, in conjunction with the steel foundries and mills, carried out a lengthy investigation, to determine the best means of producing this material, the compositions to be used for the steels, and the method of casting and heat-treating. Large castings and forgings were cut up and test pieces taken out in many directions and positions, to determine the effects of various factors.

These difficulties in obtaining large masses of steel having the desired physical properties, increase rapidly as the sizes go up. If the steel mills are asked whether they can provide a rotor forging, say, 55 or 60 in. in diameter, and weighing some 60,000 or 80,000 lb., they will assent at once. If we begin to inquire about tests, they are quite willing to accept fairly rigid specifications, but will want to locate the test bars at the ends of the forging, where there has been a considerable amount of forging work done; when we insist on locating these test bars in the large diameter of the rotor, the steel mills require an easier material specification. If we go further, and wish to take the test bars out in the direction in which they tell us most, viz., in the radial direction, the steel mill will refuse, or give such specifications as are of very little value. It is such considerations as these that have forced the rotor construction along new lines in recent years. The use of heavy steel plates for turbo rotors is comparatively old, having been adopted for a number of years both in Europe and in this country, in cases where a through-shaft can be employed. In the largest machines under discussion, where rotor ventilation becomes a necessity, where the slots are deep, and where ventilation slots below the winding slots are required, the stresses in the center of the disk, with a hole through for a shaft, run up to figures which render the use of special steel advisable. Such material is somewhat hard to obtain, particularly when the mills are busy. By using a plate without a hole in the center, the stresses in this region are kept down comparatively low, and a commercial material can be used.

This construction, which is illustrated in Figs. 5, 6 and 12 of of the paper and which was first proposed by Mr. B. A. Behrend,

appears a very bold one at first sight. The solid plates are rabetted together, assembled between two flanged shaft ends, and the whole clamped together by means of large bolts located in the poles. There is no through-shaft, and the resistance to twisting of the rotor is entirely one of friction, aided by the shear resistance of the bolts. However, a little investigation showed that this was quite a feasible form of construction, a conclusion entirely born out by subsequent results. Plate steel is a commercial form in which this material can be most relied upon, and the flanges on the two stub shaft ends are thin enough to be formed by upsetting, instead of forging down, thus obtaining excellent properties in a radial direction. For the smaller radial-slot rotors, solid forgings can be satisfactorily used, and where ventilation is required this is generally obtained by grooving down the rotor in a lathe in several places, the grooves extending all the way around and communicating with axial air passages. In the solid plate constructions, these grooves are formed by milling the flat face of the plate in the region of the slots only, leaving the full thickness of the plate in the polar region. In this way the rigidity of the rotor is not impaired by the means for ventilation and an exceedingly stiff construction can be obtained.

There have been several references in the discussion to the critical speed. I am of the opinion that there are many more machines running above their critical speed than is generally believed. Machines can be made to run satisfactorily above the critical speed, but there is a considerable advantage in running below, where this is commercially feasible. This is particularly so in the case of the four-pole machine, as distinguished from the two-pole machine. In the case of the four-pole machine a short-circuited turn on one pole, for instance, will considerably unbalance a machine that is mechanically balanced, if it is running above its critical speed; on the other hand, a large percentage of the winding on one pole can be short-circuited without causing vibration, if the machine is running below its critical speed. There are also advantages in a stiff rotor for the two-pole case.

The constructions discussed here provide some very large machines running below their critical speed, and this feature is believed to be of considerable importance, and one for which it would be worth while to sacrifice to some extent electrical considerations, when necessary.

Mr. Junkersfeld has referred to the question of the collection of dirt in generators, and has drawn attention to the fact that exploring coils might be put in and the temperature rise used as a criterion for the periodical cleaning. With the more common methods of stator ventilation, the vent entrances, being limited by tooth size and duct width, are small and rather easily clogged, and the air passages are intricate; further, to clean them out the rotor must be removed and even then a thorough cleaning is difficult. In the case of the axial arrangement of ventilation

described in Mr. Lamme's paper, the vents are straight and large, and of uniform section throughout their length, and it is generally possible to clean them out without removing the rotor, by merely passing through them a wire scratch brush similar to a rifle cleaning brush.

W. J. Foster (by letter): Limitations in design are less oppressive with the selection of proper voltage. For three-phase generators of over 20,000 kv-a., that have only two poles, potential of 10,000 or 11,000 volts is probably preferable to 6600, since the problems of insulating are not so serious as the difficulties involved in a design with too small a number of slots and with conductors carrying excessive current.

The limitations in design can undoubtedly be reduced in the case of the largest two-pole generators by increasing the number of phases to six or twelve. It would probably be found in connection with a 40,000-kv-a., 1500-rev. per min., 25-cycle generator that decided advantages would result from the use of twelve phases and about 4000 volts.

The fields of the largest generators should never be wound for less than 250-volt excitation.

Mr. Lamme rightly dwells upon the desirability of an insulation that will stand temperatures as high as 125 deg. cent. It is to be hoped that the particular type of mica insulation described has raised the safe limit to that figure, and that further improvement in the use of mica or the development of some other type of insulation will raise it to a much higher figure with safe internal temperatures.

In the matter of the limitation due to the ventilation problem, the designer often has it in his power, in connection with very large (possibly not the largest) machines, to exaggerate certain features, such as the use of an extremely large air gap and stator slots left open at the gap. This can be done by deliberately increasing the axial length of the machine, thus reducing the pole face density and not increasing at all the magnetic reluctance in the air gap. Of course, such a design involves a decided increase in the amount of material used.

K. E. Czeija (by letter): Mr. Lamme has considered all points of interest in regard to modern turbo-alternator design, and after this logical separation and analysis of the different problems, a discussion of the details seems unnecessary. Nevertheless, I would like to mention a few points that seem to be worth while considering in regard to the axial ventilation problem.

Evidently, the most effective ventilating scheme will be obtained when for a minimum amount of energy required for circulating the air through the machine, a maximum amount of heat will be absorbed by this air. We will come nearest to this ideal condition when the path of the air through the machine has the least possible number of changes in the direction in which it is flowing, and moreover, when it comes in contact with those surfaces to which the heat from the inner part is conducted with the smallest possible resistance.

If the cooling air enters the machine at one side in order to be blown in an axial direction through the stator, the air gap, and the rotor, the only important question will be the length of the paths along which the air may be moved without the temperature difference between the air and the surrounding metal parts becoming too small to be effective. For the case in which the limit set by this principle will be exceeded, it will be necessary to divide the cooling air paths in two or more parts.

It has been proved that the introduction of radial ventilating ducts wider than the usual ½ to ¾ in. (12.7 to 19 mm.) will produce local losses due to unequal flux distribution in axial direction along the stator core, unequal dielectric stresses in the insulation material, whirling of the air, and cause noise, in addition to which dirt may collect at some places.

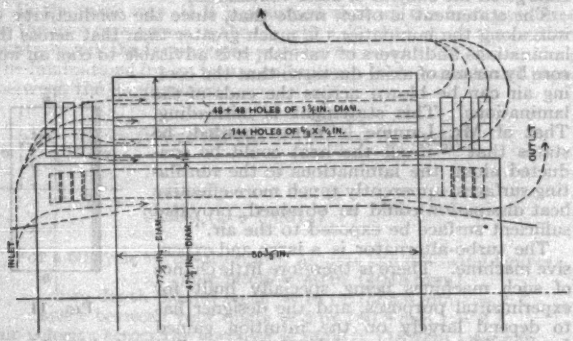


FIG. 10

In order not to subdivide the stator iron more than absolutely necessary, and in order to get the smallest distance between bearings, where it is advisable to adhere to the axial ventilation principle, the number of radial air ducts should be kept as small as possible.

The sketch herewith (Fig. 10) represents a very interesting example of the straight axial ventilation principle applied on a 7500-kv-a. three-phase turbo-alternator* for 2200 volts, 70 per cent power factor, 50 cycles and 1500 rev. per min. In addition to the values shown in the sketch, the following data will be of interest on account of the length of this machine, representing probably the maximum obtainable length of undivided axial air paths.

*Built in Germany.

Running without armature current and a field current corresponding to full load zero power factor, the following losses and temperatures were tested:

Iron loss 190 kw.

$I^2 R$ field 30 kw.

Windage 42 kw.

At the total air quantity of approximately 19,000 cu. ft. (538 cu. m.) per minute, the incoming air is 20 deg. cent., the outgoing air 50 deg. cent.

Stator iron at the inlet side 27 deg. cent.

" " " " outlet " 83 deg. cent.

Alexander Gray (by letter): A clear conception of the subject of ventilation is of the utmost importance to the designer of electrical machinery and particularly to the designer of turbo-alternators, and for that reason I have considered it advisable to enlarge on the subject of axial ventilation.

The statement is often made that, since the conductivity of iron along the laminations is much greater than that across the laminations and layers of varnish, it is advisable to cool an iron core by means of axial ducts, so that the cooling air can be blown across the ends of the laminations. This statement is misleading. That of Mr. Lamme is more guarded; he states that "if all the heat could be conducted along the laminations to the ventilating surfaces, apparently much more effective heat dissipation could be obtained, provided sufficient surface be exposed to the air."

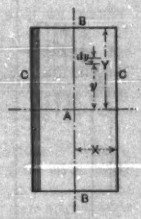


FIG. 11

The turbo-alternator is a large and expensive machine. There is therefore little chance of such machines being specially built for experimental purposes, and the designer has to depend largely on the intuition gained from a wide experience with other types of electrical machinery.

The following investigation in which the conductivity of the iron core is compared with that of the surface between the iron and the adjoining air is of considerable interest. Fig. 11 shows an iron core built up of laminations which are separated from one another by layers of varnish; the loss in this core is supposed to be uniform throughout its volume. The heat generated in the core has to be conducted to and dissipated by the surfaces B and C.

If all the heat passes in the direction Y then the watts crossing each square inch of the core at y = (watts per cu. in.) y and the difference in temperature between two surfaces a distance dy apart

$$= \frac{(\text{watts per cu. in.})\, y\, dy}{1.5} \text{ deg. cent.,}$$

where 1.5 is the thermal conductivity of iron in watts per inch cube per deg. cent. difference in temperature. The difference in

temperature between surfaces A and B for the assumed conditions is therefore

$$= \frac{(\text{watts per cu. in.})\ Y^2}{3} \text{ deg. cent.}$$

$$= T_{ab}$$

When air is blown across the surface of an iron core with a velocity of V ft. per min., the watts dissipated per square inch of the surface for 1 deg. cent. rise of the surface temperature $= 0.0245\ (1 + 0.00127\ V)$*. If then the heat is all dissipated by the surfaces B, the difference in temperature between surface B and the air $= T_b$

$$= \frac{(\text{watts per cu. in.})\ Y}{0.0245\ (1 + 0.00127\ V)} \text{ deg. cent.}$$

In the same way, if it is assumed that all the heat generated in the iron core passes in the direction X, then, since the conductivity across the laminations may be taken as 1/50 of that along the laminations for an iron core built up with varnish and paper between the laminations,

$$T_{ac} = (\text{watts per cu. in.})\ \frac{50\ X^2}{3} \text{ deg. cent.}$$

$$T_c = \frac{(\text{watts per cu. in.})\ X}{0.0245\ (1 + 0.00127\ V)} \text{ deg. cent.}$$

For a 60-cycle turbo-alternator assume the following figures:

pole pitch = 40 in. (1016 mm.)
core depth behind teeth = 14 in. (355.6 mm.) = $2\ Y$
space between vent ducts = 2 in. (50.8 mm.) = $2\ X$
air velocity across the surfaces = 6000 ft. (1829 m.) per min.

Then $T_{ab} = 17$ deg. cent.
$T_{ac} = 17$ deg. cent.
$T_b = 33$ deg. cent.
$T_c = 4.7$ deg. cent.
$T_{ab} + T_b = 50$ deg. cent.
$T_{ac} + T_c = 22$ deg. cent.

That is to say, for the assumed conditions the thermal conductivity along the laminations and across the surface is only 43 per cent of that across the laminations and surface; there is evidently still a strong case for radial vent ducts.

In the actual case there is of course a larger loss per unit volume in the teeth than in the core behind the teeth, and in some other respects the case discussed does not correspond exactly with that of the turbo-alternator core, but the argument has been worked

*Ott; *Electrician*, March 7, 1907.

up to show that, compared with the surface resistance between the iron and the air, the thermal resistance across the laminations is relatively not very large.

Since it is necessary to keep the insulation cool, it would seem that axial ventilation along the air gap is desirable, but such ventilation should be combined with circumferential ventilation in order to keep the bulk of the core cool. Fig. 12 shows a method of ventilation which has advantages for machines that are not too large; for long machines the air for circumferential ventilation should be sent in from both ends of the machine; that for axial ventilation along the air gap should also be sent in from the ends and then led out through a wide duct in the center of the core. In the diagram shown there are ten short paths through the core, and with ducts spaced so that the blocks of iron are 2 in. (50.8 mm.) thick and with a core density of 60,000 lines per sq. in (9300 lines per sq. cm.) at 60 cycles, it is possible to get 100 cu. ft. (2.83 cu. m.) of air per min. through the machine per

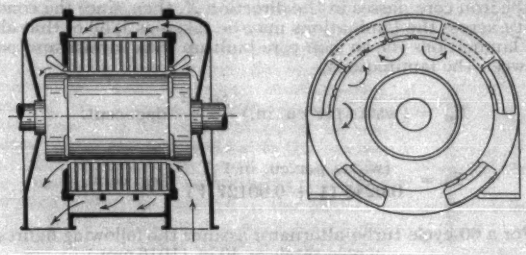


FIG. 12

kilowatt loss without the velocity in the ducts exceeding 4000 ft. (1219 m.) per min.

The statement in Mr. Lamme's paper that the temperature of the iron does not limit the machine, but rather that of the insulation, requires some modification. The above investigation shows that at certain points in the body of the core the temperature may be 20 deg. cent. higher than that of the surfaces of the vent ducts, and we are asked to approve of surface temperatures of the order of 100 deg. cent. Such temperatures are not safe unless non-aging iron is used for the core, and the writer would like to know if time tests are made on the iron used for turbo-alternators at the temperatures which may be expected in the body of the core when the machine is in operation, in order to determine whether or not the iron loss increases with time.

It has been evident for some time that the measurement of temperature rise by thermometer, and a guarantee of 40 deg. cent. rise, have become obsolete, and yet a temperature rise of 80 or

100 deg. cent., the temperature to be measured by resistance or by a resistance thermometer, is unsafe unless mica insulation is used. It would therefore seem that the purchaser of a turbo-alternator has to depend largely on the reputation of the manufacturing company, rather than on a written specification, to ensure satisfaction, and also that ordinary witness tests are of little value compared with tests run over a long period of time. That being the case, the writer would like to have an opinion as to what kind of clause should be inserted in specifications in order to protect both the purchaser and the manufacturer and also what tests should be considered as satisfactory for acceptance of the machine. The purchaser should be protected against deterioration of the insulation and increase of the core loss due to high operating temperatures and yet the manufacturer should not be required to wait indefinitely for his money.

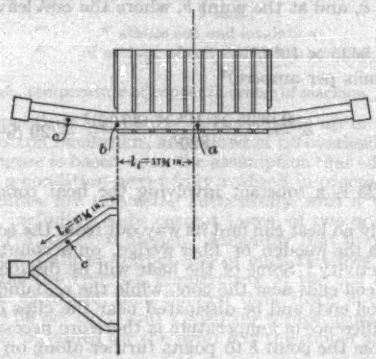


FIG. 13

Bradley T. McCormick (by letter): Under the subject of temperature rise, Mr. Lamme refers to machines in which the stator teeth are hotter than the copper. Such a condition might exist at low loads, but I am inclined to believe that on turbos of usual design, the hottest spot in the stator at full load is the point *a* (see Fig. 13), the copper in the top of the slot in the center of the machine; and that the most difficult problem in stator design is to keep this point at a temperature low enough to prevent injury to the insulation. On machines of the turbo type it is hardly probable that the teeth can ever be hotter than the copper in the center of the machine, unless the iron is so poorly ventilated that the teeth and core are much hotter than they should be, in which case the machine will not meet the guaranteed temperature rise.

Suppose, for the sake of argument, that the teeth are hotter than the copper. Then no heat flows from the windings into the iron, but all the heat generated in the coils must flow along the copper to the coil ends, and there be carried away by the air. It can be shown that in order to force the heat to travel along this path, the difference in temperature between the copper at the center of the machine and the outside surface of the coil ends, will be so great that the resulting temperature of the copper at the center of the machine, and the teeth, (which we have assumed to be hotter still,) will be quite beyond the limit of safety.

Take an example from a machine which is operating successfully. We have a total embedded length of stator copper of 35½ in. (901.7 mm.) working at a density of 820 cir. mils per ampere. We will first assume that there are no eddy currents. If all the heat flows along the copper and out at the ends, we have, as the difference in temperature between the copper in the center of the machine at a, and at the point b, where the coil leaves the slot,

$$T_i = \frac{0.0625 \times 10^6\, l_i^2}{(\text{cir. mils per ampere})^2}$$

$$= \frac{0.0625 \times 10^6 \times (17\tfrac{3}{4})^2}{820^2} = 29 \text{ deg. cent.}$$

where 0.0625 is a constant involving the heat conductivity of copper.

Practically no heat can find its way out from the coil to the air gap through the wooden or fiber wedge, on account of its poor heat conductivity. Some of the heat will be dissipated at that part of the coil ends near the core, while the remainder will flow along the coil ends and be dissipated near the clips or U bends. A further difference in temperature is therefore necessary to pass the heat from the point b to points further along on the ends of the coils, where it can be carried away by the blast of air. This temperature difference it is extremely difficult to calculate, but it can be roughly estimated. If we assume for simplicity that the end connection temperature drops uniformly from the iron to the clips, then the temperature of the point c will be the mean temperature of the coil ends, and we can consider the problem as if all the heat generated inside the slots were conducted to the point c midway between the iron and the clips, and dissipated at this point. We shall then have

$$T_e = \tfrac{1}{2}\, T_i \frac{l_e}{l_i} = \tfrac{1}{2}\,(29)\,\frac{27\tfrac{1}{4}}{17\tfrac{3}{4}} = 22.3 \text{ deg. cent.}$$

where T_e is the difference in temperature between the points b and c.

A still further temperature difference is necessary to pass the entire stator copper loss through the insulation on the ends of the coils. From the thickness and quality of insulation, and the surface exposed to the air, the temperature drop across the coil end insulation is estimated at 13 deg. cent. for this machine.

Assume now that the air blowing on the coil ends is at 25 deg. cent. and that the blast is sufficient to limit the running temperature of the surface of the coils at *c*, to 40 deg. cent. This assumption of only 15 deg. cent. rise of coil surface exposed to air is certainly as low as could be expected.

We can now calculate the temperature of the copper at the center of the machine, which will be as follows:

29	deg.	temperature	drop	between	*a* and *b*
22	"	"	"	"	*b* and *c*
13	"	"	"	across	coil end insulation
40	"	"	of surface	of coil ends	while running
104	deg. cent., temperature of copper in center of machine.				

This temperature of 104 deg. cent. is quite up to the limit of safety for cotton insulation, and allows of no overload. Furthermore, this figure is based upon the assumption that eddy currents are absent, a condition never fully realized in practise. A great many machines are operating successfully with a total stator copper loss, including eddy current losses, of two or three times the normal I^2R, or even higher. Assuming that in our example we have a total stator copper loss of only $1\frac{1}{2}$ times the normal I^2R, and that the running temperature of the coil ends is still 40 deg. cent. as before, then the first three items in the sum will be increased 50 per cent, and a resulting temperature of 136 deg. cent. will be obtained for the point *a* in the copper at the end of the machine.

If, as Mr. Lamme claims, the teeth are hotter than the copper, then the teeth of this machine must be at a temperature greater than 136 deg. cent. Such could only be the case if the machine were insufficiently ventilated, and the excessive iron temperature would show up on test, and the machine would be rejected.

The turbo chosen in this example is quite typical, and the results obtained from these calculations are so extreme that one may infer that any other turbo treated in a similar manner will also show a temperature unreasonably high.

It would therefore appear hardly possible that the teeth of a turbo-generator can run hotter than the copper in the center of the machine, and the machine still be at all acceptable, although it is of course possible that those portions of the winding near the ends of the core may be cooler than the teeth. With sufficient ventilation to limit the tooth temperature to 40 or 50 deg. cent. rise by thermometer, the extremely high copper temperatures, which have been calculated above, are prevented by the flow of heat from the copper through the insulation into the iron, so

that although the hottest point *a* may still be over 40 deg. cent. above the air, it will, however, be at a safe temperature that will not injure the insulation.

The above discussion has a very important bearing on the question of insulation, for if most of the heat from the windings is conducted to the coil ends, and there carried away by the air, the designer is justified in resorting to very thick slot insulation; but if the cooling of the winding is largely dependent upon the ability of the heat to pass through the slot insulation into the iron, as seems to be the case, then an increase in slot insulation involves higher temperatures in the stator copper, which may induce the designer to reduce the factor of safety of his insulation, with invariably disastrous results. These conditions are especially true in connection with machines of high voltage, and form one of the limitations to the continued increase in size and voltage of turbo-generators.

These difficulties naturally lead to the discussion of the advantages of mica insulation. Mica, on account of its ability to resist heat, is largely employed in turbo-generators, but as a conductor of heat it is only from 50 per cent to 70 per cent as good as varnished cambric, depending upon the way in which the mica is built up. Due to this fact, and also to the fact that mica is very expensive, the designer may be tempted to use a thin mica insulation, and feel that he is justified in so doing by the high dielectric strength of mica. Such a practise only invites the insulation difficulty to which Mr. Lamme refers, static discharges between the coils and the iron.

It is extremely difficult to apply mica insulation in such a way as to exclude air pockets. The pressure gradient at which air breaks down is quite variable, depending upon whether a large or small quantity of air is under stress, but for small air pockets in the insulation and dense air films lying in contact with surfaces, corona will form at a pressure gradient somewhere in the neighborhood of 200 volts per mil. With a specific inductive capacity of about 6 for mica, it therefore requires an insulation distance between copper and slot sufficient to give a mean pressure gradient, in round numbers, of 35 volts per mil, based upon the Y voltage, that is, the line voltage divided by $\sqrt{3}$.

Any attempt to decrease the insulation beyond this point will result in the formation of static in the enclosed air pockets, as well as at the points where the coils emerge from the slots, both inside the ducts and at the ends of the machine. In machines which have not been properly insulated the presence of static can sometimes be detected, when running on full voltage, by a distinct odor of ozone near the terminals where the voltage to ground is highest. This of course only applies to engine type machines or waterwheel machines whose speed is low enough to prevent the windage from blowing away the ozone as fast as it is formed, and thus making it impossible to detect its presence.

Jens Bache-Wiig (by letter): Mr. Lamme's paper shows, I think, that a large high-speed turbo-alternator can now be built sufficiently safe electrically to put it on a par with, say, a low-speed alternating-current generator with mica-insulated armature coils and asbestos-insulated field coils. As stated in the paper, this is due principally to the improved method of ventilation, to the insulating material adopted and to the electrical design as a whole, especially as regards short-circuits.

Concluding, Mr. Lamme asks if the temperature problem inherent with these machines may be considered due to the design being too much forced.

It seems to me that this problem is solved very satisfactorily by the adoption of mica insulation. I would like to add as my opinion that the development of low-speed electrical machinery will not be completed until the same kind of insulating material has been adopted for these machines as well.

In one point, however, I do think the construction is stretched too far, and that is with regard to the mechanical design.

As an example is given a 5000-kv-a. two-pole 3600-rev. per min. 60-cycle generator with a rotor diameter of 66 cm. This gives a peripheral speed of 124.3 m. per sec. It is stated that the core is designed for a very considerable margin of safety, and is actually tested at overspeeds which give about 152.3 m. per sec. peripheral speed. This means that the rotating part has been tested at about 22.5 per cent overspeed.

Compared with general practise in turbo-alternator design this may be called "a very considerable margin of safety," but why is it that such machines are designed so very close to the bursting point, as compared with other electrical machinery? The answer that it can not be done any other way does not seem satisfactory.

Take for instance a waterwheel-driven alternating-current generator. The design of such a machine is not considered safe, unless it will withstand successfully the runaway speed of the turbine. Now, if this is of such importance with regard to one type of turbine-driven alternators, why does it not hold true for the other type?

If anything, the case seems to be slightly worse for the steam-driven turbine than for the water-driven turbine, as the inertia of the rotating element is usually smaller for the former and it will therefore more quickly attain a high speed.

The reliability of the regulating devices cannot be any greater for the steam turbine than for the water turbine.

Furthermore, a waterwheel-driven generator is often specified to withstand this runaway speed of the turbine, starting with maximum excitation, at no load.

As compared with this, many a steam turbine-driven generator has been designed which at normal speed and no load would not safely withstand the voltage obtained at maximum excitation.

It seems to me that there ought not to be any such great dis-

crepancy between the designs of two such closely related types of machines. Either the steam turbine-driven generator is not designed with enough margin of safety, or the design of the water-turbine-generator is being unnecessarily handicapped. Experience has shown that the latter is not the case. What about the safety of the other?

F. H. Clough (by letter): Mr. Lamme has given a very able and comprehensive review of the design of large turbo-generators, and I should like to add my appreciation of the way in which he has discussed the difficulties that have been encountered, and described the methods that have been adopted to overcome these difficulties. In most points I can thoroughly endorse his conclusions.

In discussing the paper I should like to suggest that the author has not given sufficient prominence to the possibility of running generators above the critical speeds of their shafts, as in the first portion of his paper several forms of rotor construction are discussed and all these lead up to the solid forged rotor with slots cut out in the periphery.

The company with which I am associated has for some years past been building high-speed machinery (mostly for 3000 revolutions) in which the critical speed is about half the running speed, and this practise has proved itself to be entirely satisfactory.

It was necessary in the first case to design a bearing which would give a slight amount of freedom at one end of the shaft to avoid danger when passing through the critical speed, and, with this precaution, no trouble has been experienced, and I am inclined to think that the running of a machine with a low critical speed is better than a stiff shaft machine, provided the same amount of care be taken in balancing in both cases. When machines are designed for the highest possible outputs and speeds, the critical speed of even a solid rotor tends to become uncomfortably close to the normal running speed—and in some extreme cases may be even below it.

It has been suggested that the shock caused by an accidental short-circuit might cause trouble to a machine with a low critical speed, but no such effect has been noticed in practise.

The use of a small diameter shaft with a low critical speed makes a much more consistent design of the rotor, as on account of the comparatively small torsional forces and the high rubbing speeds of the bearings the diameter of the shaft is usually small in the journals. Further than this, the use of a small shaft gives opportunities for ventilation of the rotor which cannot be obtained with a solid forging, and also allows a suitable depth of rotor punching to withstand the centrifugal forces which occur.

B. G. Lamme: There seems to be an impression among some of those who have discussed the paper that I am advocating new and higher temperature limits than we have at present. I had no intention of giving such an impression, but simply meant

to bring out that we have, in some cases, temperatures of 125 deg. cent. at present and that we must therefore consider such temperature limits from the commercial standpoint. We have had relatively high temperatures in practise for a good deal longer than many people think. Numerous machines which have been running for years attain temperatures of 100 deg. cent. or over at the hottest parts, although insulated with fibrous materials, and in many cases these machines have had a comparatively long life. However, where the actual temperatures have been materially higher than 100 deg. cent. we have had to protect them by the use of the mica class of insulating materials.

There has been great misunderstanding regarding the actual highest temperature obtained in commercial machines. When we say that 90 deg. is the limiting temperature for fibrous insulation, we should really say that it is the limiting temperature, by certain specified methods of measurement. In addition to this measured temperature, we must consider the internal drop which brings the actual temperature of the hottest part to 100 deg. or even higher.

I have had very considerable experience with mica insulations, both in high-voltage armatures and in field coils, in generators and in other kinds of apparatus; and, based on my experience, I am willing to state that mica insulation, well put on, is as safe at 125 deg. cent. as ordinary fibrous insulations at 90 deg. cent., on the basis of the same methods of measurements that we ordinarily use, such as thermometer, resistance, and exploring coil or thermocouple methods.

Turbo-generator fields furnish one fairly accurate means for determining permissible limiting temperatures. In the parallel type of slot rotor described in the paper, the field windings are completely embedded in iron and, in some cases, all parts of the winding have about equal temperature rise. In such cases, therefore, the resistance measurement of the field gives a fairly reliable measure of the true temperature obtained. In such fields I have seen fibrous insulations worked at 125 deg. cent for several months before being mechanically ruined. This gives an idea of what some fibrous insulations will stand. In other cases, a temperature of 100 deg. cent. or slightly higher has been found in machines which have stood up for many years. In the case just mentioned, where 125 deg. with fibrous insulation was attained, the field was eventually rewound, with mica in the slots and asbestos between turns, and has stood up without injury, as far as has been determined, up to the present time. In fact, it has run considerably above the 125 deg. cent. temperature at times, as the load conditions were increased after the field was rewound. A number of cases are known where, with mica insulation, 150 deg. cent. has been attained for long periods without any apparent injury.

Available data thus indicate that, where reasonably accurate measurements of the *hottest* part of the winding have been made,

we have actually encountered much higher temperatures than usually supposed. Our general ideas of 80 to 90 deg. cent. limits are therefore based upon relatively crude methods of measurement. It has long been known by designers that, in designing certain windings, we must actually insulate for considerably higher temperatures than the ordinary methods of measurement will indicate.

Referring briefly to some of the features brought out in the discussion, Mr. Torchio mentioned the use of a metallic sheath over the armature winding. I will say that this has been considered at various times, but one difficulty lies in the fact that e.m.fs. will be generated in this sheath, necessitating that it be carefully insulated. Moreover, in general, it is necessary to laminate the conductors in the coil to eliminate eddy currents. A continuous sheath would be subject to such eddy currents, and, as this sheath would be considerably wider than the conductors in the coil, in many cases it would be subject to excessive losses due to such eddies.

In reference to the short-circuit tests referred to by Mr. Torchio, I do not think that all the difference shown is accounted for by the difference between the parallel and radial slot rotors. The arrangement of the end windings in the machines was quite different in the two cases. The number of conductors per slot in one case was only two-thirds that of the other, while the number of conductors in series was also considerably smaller. All these differences, combined, should account for a considerable difference between the two machines, but not nearly as much as Mr. Torchio has shown. However, I am not prepared to account for all the difference, as I do not know all of the conditions.

Mr. Fechheimer evidently did not understand my remarks in regard to making the regulation poorer by doubling the rating. I do not believe that I really implied that we could double the rating on a given machine. I simply assumed a double rating to indicate, in a general way, how the regulation and the short-circuit current would be affected. This was simply an illustration, not a statement of general practise.

Mr. Fechheimer raised the question as to how I measured an air velocity of 10,000 ft. (3048 m.) per minute in some parts of the air paths of turbo-generators. I will say that this was not measured directly, but was determined by measurement of the total quantity of air per minute fed into the machine, and the cross-section of the smallest openings through which this air had to flow. This, in some instances, indicated an air velocity in certain restricted parts of the path which exceeded 10,000 ft. per minute.

Mr. Junkersfeld suggests that 85 deg. should be the limit for fibrous insulations. This temperature is probably based upon his experience with measurements at the hottest part which could be found, by exploring coil or otherwise, on the outside

of the insulation of high-voltage coils. If this is the case, I agree with him in general, except that possibly his figure is too high for very high voltage machines, in which there is possibly an internal drop of 20 deg. cent. from the outside surface of the insulation to the hottest part inside. This would bring the temperature up to 105 deg. cent. on my assumptions, which would be right on the ragged edge.

Mr. McCormick criticises my statement that the stator teeth can be hotter than the copper. In the general discussion of flow of heat and temperature rise in my paper, I was dealing largely with the general problem. What I wished to bring out was that, in the turbo-generator, the temperature was likely to be much higher at the center of the machine than in ordinary machines. In some cases, with ordinary machines, it was found that, even at full load, the temperature of the armature teeth was higher than that of the inside copper. However, this has rarely been found true in turbo-generators, although a few instances of this sort have been noted. In the example cited by Mr. McCormick, where the temperature of 104 deg. would be attained in the copper at the hottest part, he then adds a very considerable amount, in addition, for rise due to eddy currents. However, if the winding were so completely laminated, or so arranged that eddy currents were practically absent, then the result indicated in his example could be a possible one, although mica insulation would be required. Such cases, however, are unusual, and were brought into my paper simply as one extreme condition. I did not intend to give the impression that tooth temperatures higher than copper temperatures were common at heavy loads.

Mr. McCormick states that mica is a much poorer conductor of heat than varnished cambric. I will take some exception to this point. I will admit that mica insulation, as usually built up, is liable to be poorer than varnished cambric and such materials, as the mica laminae may not be in contact with each other. But when mica insulation is built up by some of the new processes, as referred to in my paper, where it is made almost bone hard, it is practically as good a heat conductor as varnished cambric, or other materials.

Mr. Bache-Wiig brings out the question that the overspeeds allowed in turbo-generators are very small compared with those in waterwheel practise, and thinks that we have not placed the limit high enough.

In answer to this, I will say that in the waterwheel-driven generator, the overspeed is placed at the runaway speed which could be attained by the waterwheel if the load were thrown off suddenly. In the case of the turbo-generator units, the overspeed attainable by the engine, in many cases, is so high that it is impracticable to build either a turbine or a generator which can stand such speed. This being the case, and as automatic cut-offs therefore must be relied upon, it then becomes a

question as to what overspeed should be allowed before the cut-off can act positively. It is generally conceded by turbo manufacturers that the automatic cut-off must work under 15 per cent overspeed, and on this basis, 22½ per cent overspeed, as referred to by Mr. Bache-Wiig, is ample margin. In general, if it will not work at this speed, it will not work at all.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

TEMPERATURE AND ELECTRICAL INSULATION

BY C. P. STEINMETZ AND B. G. LAMME

The problem of permissible temperature limits in electric apparatus is largely that of the durability of the insulation used. As this may consist of materials of widely varying heat-resisting qualities, the problem resolves itself into one of consideration of the properties of the materials themselves.

The durability of insulation may be considered from two standpoints, the mechanical and the electrical. Tests and experience have shown that temperatures which may ruin the insulation, from a mechanical standpoint, may not radically affect its dielectric strength. This is particularly true with moderate voltages, where the insulation serves largely as a separating medium. The purpose of the insulation usually is two-fold: First, it must serve to separate, mechanically, the electric conductors from each other, and from other conducting structures, and second, it must withstand the voltage between the electric conductors, and between the electric circuits and other conducting parts. In lower voltage apparatus, usually only the former function applies, as the mechanical separation is more than sufficient to withstand the voltage used. The dielectric strength of the material is, however, of first importance in high-voltage apparatus.

A great majority of the electrical "breakdowns" on low-voltage apparatus is due to mechanical weaknesses, as far as the temperature problem is concerned; that is, high temperatures may make the insulation brittle, or crisp, so that it may flake off, or powder, or crack, or be crushed by mechanical action, thus allowing the conductors to make contact with each other or with adjacent conducting material.

The "life of insulation" is an indefinite term and must be defined in time, mechanical strength, absence of foreign materials of a conducting nature, etc. Almost all insulating materials will be somewhat affected in time, and many of them tend to become dry and brittle. The rate at which deterioration occurs with any given material, is some complex function of the temperature and of other conditions.

Classes of Insulations

Insulations may be classified under three headings, depending upon their heat-resisting properties. However, all such classifications must be relative, for no absolute limit can be fixed, as there is no definite point at which injury or destruction can be said to take place.

The usual insulating materials can be considered as included in three general classes:

Class A. This includes most of the fibrous materials, as paper, cotton, etc., most of the natural oil resins and gums, etc. As a rule, such materials become dry and brittle, or lose their fibrous strength, under long continued moderately high temperature, or under very high temperature for a short time.

Class B. This includes what may be designated as heat-resisting materials, which consist of mica, asbestos, or equivalent refractory materials, frequently used in combination with other supporting or binding materials, the deterioration of which, by heat, will not interfere with the insulating properties of the final product. However, where such supporting or binding materials are in such quantity, or of such nature, that their deterioration by heat will greatly impair the final product, the material should be considered as belonging to class A.

Class C. This is represented by fireproof, or heat-proof materials, such as mica, so assembled that very high temperatures do not produce rapid deterioration. Such materials are used in rheostats and in the heating elements of heating appliances, etc.

All the above are relative terms. The first class, for instance, represents materials which are really more or less heat-resisting, but which deteriorate at lower temperatures than those in the second class, which are defined as heat-resisting. Also, the fireproof materials of the third class are not strictly heat-proof or fireproof, but will simply withstand very high temperatures for relatively long periods without undue deterioration.

In class A, the materials appear to have a very long life (or an almost indefinitely long life, aside from mechanical conditions) if subjected to ultimate temperatures which never exceed 90 deg. cent. Also, they appear to have a comparatively long life even at ultimate temperatures as high as 100 deg. cent. At materially higher temperatures than 100 deg. cent., the life is very greatly shortened, and temperatures of 125 deg. cent. will apparently ruin the insulation, from a mechanical standpoint, in possibly a few weeks, if such temperature is maintained steadily. However, for low voltages, the insulating qualities may still be very satisfactory, even at this temperature, and therefore the destruction of the insulation is purely one of injury or breakdown from the mechanical standpoint, as stated before. Tempera-

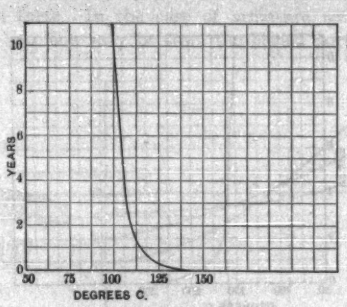


FIG. 1

tures as high as 160 deg. cent. on such insulations for a considerable period may not entirely destroy their insulating qualities, although, mechanically, such temperatures appear to be impracticable, except for very short periods.

In order to illustrate the relation between the possible life and temperature of class A insulation, Fig. 1 is shown. This must not be taken as representing actual results, but is simply intended to illustrate, in a merely approximate manner, the very great shortening of the life of insulation by increase in temperature.

It may be assumed that at very high temperatures, the insulation will have practically the same life, in actual hours of high temperature operation, whether the temperature is applied continuously or intermittently. For example, if an insulation has 10,000 hours life with a certain high temperature continuously

applied, it is assumed that it will also stand the same temperature for 10,000 hours in short periods, provided the intermediate temperatures are low enough to represent an indefinitely long life. It is probable that under the intermittent condition, the life will really be slightly greater, due to the fact that depreciation will be largely mechanical, and the insulation may "recover," in some of its mechanical characteristics, after each period of high heating.

If, therefore, high temperatures are reached intermittently, with intermediate periods of lower value but still high enough to shorten the life of the insulation, it may be assumed that the total life of the insulation is the resultant of the life under the two temperature conditions.

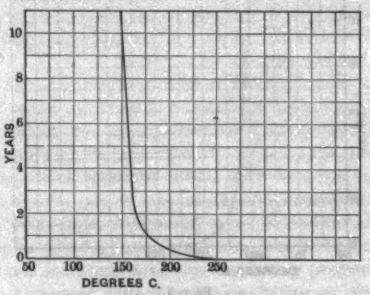


FIG. 2

In heat-resisting materials, such as those of class B, temperatures of 125 deg. cent. are comparable with 85 deg. cent. or 90 deg. cent. in class A, and 150 deg. cent. in the former is comparable with 100 deg. cent. in the latter. Fig. 2 illustrates merely approximately the life-temperature curve of such insulations. As in Fig. 1, this should not be taken as an exact representation of the actual life. Due to the greater heat-resisting qualities of such materials, it appears that relatively higher temperatures are not as quickly harmful as in the first class.

In class C materials, it is difficult to give any reasonable indication as to the limits of temperature, except that very high temperatures (practically up to the point of incandescence) are found in some heating appliances.

Temperatures and Flow of Heat

As the insulation, in itself, is not usually the seat of generation of loss or heat, it is the temperature of adjacent materials which must be considered in defining the conditions in the insulation. The temperatures of the adjacent materials should therefore be considered only in so far as they affect the insulation itself, and where such temperatures do not affect the insulation, or the life of the apparatus, or its normal perfomance, they are immaterial.

Considering the influence of the temperatures of the adjacent media, the direction and amount of heat flow must be taken into account, as the maximum temperature in the insulation is dependent upon these. In the case of armature windings, for instance, the heat flow may be from the buried portion of the

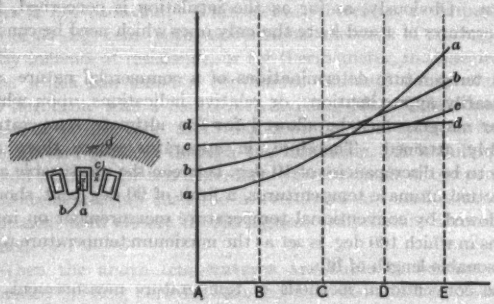


Fig. 3

coils toward the end windings. It also may be from the buried copper through the insulation to the armature teeth, or there may be a reverse heat flow from the iron to the copper, depending upon the various factors of construction, heat conductivity of the materials, amount of heat generated in the various parts, ventilation, heat dissipation, etc.

Depending upon conditions of heat flow and distribution, various methods of temperature determination may be used. No method is accurate, unless all the conditions of heat flow are accurately known, which is never the case in commercial machines.

The difficulties in the problem of commercial temperature determination are illustrated by Fig. 3.

In the figure, *a* represents the temperature inside an armature coil, *b* the temperature between the insulation and the iron of an armature tooth, *c* that in the body of the tooth, and *d* that in the body of the core at some point back of the coils and teeth. Let the temperatures at no load be represented on the ordinate *A*. Then, at some load, represented by ordinate *B*, the relations of the various temperatures have changed. At *C*, *D* and *E*, there are still greater changes, depending upon the heat generation and distribution. If the rated capacity of the machine is at *E*, for instance, then the armature copper is hotter than the iron, while if rated at *B*, the reverse would be true. Obviously, no rule can be formulated to cover these various conditions in different machines, nor even in a given machine, unless all the heat generation, distribution, and dissipation characteristics are known. Obviously, as far as the insulation is concerned, the temperatures of *a* and *b* are the only ones which need be considered.

All temperature determinations of a commercial nature are necessarily approximations, or relative indications, upon which proper margins must be allowed for the ultimate temperature possibly attained. Therefore, in apparatus where there are liable to be discrepancies of 10 deg. between the measurable and the actual ultimate temperatures, a limit of 90 deg. cent. should be allowed by conventional temperature measurement on insulations in which 100 deg. is set as the maximum temperature with a reasonable length of life.

The conventional methods of temperature measurement, as by resistance, and by thermometer, do not usually give the maximum temperature, but give either the average, or the outside surface, values, and, when measuring the temperature by these methods, which are the only ones generally applicable, an allowance must be made in windings for possible local higher temperatures. These methods apply especially to those machines of moderate or low voltages in which the insulation is relatively thin, so that the heat gradient from the inside copper to the outside surface is small. Also, they apply particularly to those machines in which the conditions of ventilation are not normally difficult, and in which a fairly thorough distribution and dissipation of heat occurs among the various parts, such as in ordinary direct-current armatures, induction motor primaries, stators and rotors of moderate speed alternators in which the width is relatively small compared with the diameter, etc.

As the ultimate temperatures obtained by the apparatus depend upon its rise above the room temperature, or that of the cooling medium, and as such temperatures may vary over a wide range, it is not practicable to specify or guarantee ultimate temperature of apparatus without also specifying the elements upon which it depends. This, therefore, results in specifying the temperature rise in relation to that of the cooling medium.

While most apparatus operates at materially lower cooling temperature than 35 deg. cent. to 40 deg. cent., yet such temperatures are sometimes reached for considerable periods of time in steam stations, and it appears therefore as justifiable to choose the permissible temperature rise, such that, at room temperature of 35 deg. cent. to 40 deg. cent., an ultimate temperature of 85 deg. cent. to 90 deg. cent. by conventional methods of measurement is not exceeded. This means, therefore, a temperature rise of 50 deg. cent. with conventional methods of testing, such as by increase of resistance, or by thermometer, in those insulations which can stand a continuous ultimate temperature of 100 deg. cent. with a comparatively long life. This allows an excess of 10 deg. cent. to 15 deg. cent. for local spots, or for the temperature gradient through the insulation. A less allowance should be made for this difference when methods of temperature measurement other than the conventional are used, and which approach more closely to the highest temperature actually attained.

When the above temperatures are liable to be materially exceeded for long periods, heat-resisting insulation of class B is recommended. With such materials, a temperature of 125 deg. cent. is comparable with 85 deg. cent. to 90 deg. cent. in the materials of class A. Therefore, on this basis of a room temperature at 40 deg. cent. or 45 deg. cent., rises of 85 deg. cent or 80 deg. cent. should not be considered harmful. However, in those special cases where the conventional methods may not sufficiently approximate local high temperatures, as may be the case in large turbo-generators, or in wide core alternators of large capacity, the rises of 80 deg. cent. or 85 deg. cent. should not be specified by resistance or thermometer, but preferably some lower temperature such as 50 deg. cent., thus allowing a very considerable margin for local higher temperatures. In such apparatus with the higher temperatures, which require class B insulation, there is liable to be less uniformity of heat distribution.

If special methods of temperature measurement, such as exploring coils or thermocouples, are used in such apparatus, the temperature limit of 125 deg. cent. should be considered, and not the conventional 50 deg. cent. rise. In those machines of this class which have relatively thick insulation, and consequently may have a high heat gradient between the copper and the iron (depending upon how much heat is flowing from the copper to the iron), an ultimate temperature of the inside insulation of 150 deg. cent. is considered as the limit, this being comparable with 100 deg. cent. with insulations of class A.

In certain classes of apparatus which are artificially cooled by air from outside the room, the cooling is accomplished partly by dissipating heat to the artificial air supply, and partly by dissipation into the surrounding room. If the temperatures of the cooling air and of the room are widely different, the resultant of the two temperatures should really be taken as that of the cooling medium.

The variation of the temperature rise has heretofore been considered as having a definite relation to the temperature of the cooling medium. However, it appears that it does not follow any definite simple law, but it is sometimes positive and sometimes negative, so that no satisfactory correction for room temperature is possible at present. It is therefore desirable to make the temperature tests at a room temperature as near as possible to some specified reference temperature, so as to make any temperature correction negligible. The reference temperature in the guarantees should therefore be such as can easily be secured; that is, it should be the average temperature of the places at which the apparatus may be operated. This is from 20 deg. cent. to 25 deg. cent., and as it is easier to raise than to lower the room temperature, the upper figure is advisable as a reference value. This reference temperature therefore should be chosen as 25 deg. cent., which is in accordance with the previous A.I.E.E. standard.

Measurement of Temperature

In the conventional methods of temperature measurement, by thermometer, and by resistance, many conditions should be taken into account, and good judgment is required, in all cases, or fallacious conclusions may be obtained.

There are many conditions which affect the accuracy of both the resistance and the thermometer methods of measuring temperature. The resistance method measures only the average

temperature rise, and not that of local hot spots. However, it measures the internal temperature of windings, and therefore no correction is required for the temperature gradient through the outside insulation. The proposed margin between the result by the conventional method, and the actual temperature, can therefore be allowed, in the resistance measurement, as the difference between the warmer and the average temperatures in the windings. In the resistance method of measurement, the rate of transfer of heat from one part of the winding to another will not greatly affect the result, as the measurement indicates an average temperature, which would be obtained if the heat were equalized throughout the winding. However, the rate of flow of heat from the windings through the outer insulation to other parts will affect the temperature measurement by resistance, and preferably the measurements by this method should be taken during operation, in those parts where this is practicable, as in field coils, and some other instances. In those parts where the resistance cannot be measured during operation, this should be done as quickly as possible after shut-down, and the time taken to shut down the apparatus should not be unduly long. Preferably, during shut-down of rotating apparatus the normal current should be maintained on the apparatus until at least a relatively low speed is obtained. This would represent only an average condition, as the ventilation at lower speed is very greatly decreased, while the losses in the windings will remain normal, thus tending to give an increased temperature in the windings. It would be difficult to fix any definite rule which would give the exact temperature conditions during shut-down.

In the measurement of temperature by thermometer, considerable judgment is required. Wherever possible, the temperature should be taken during operation, but the thermometer with its pad should be so placed that it does not interfere with the normal air circulation. In thermometer readings, as usually obtained on windings, the heat gradient through the insulation must usually be allowed for, this being 10 deg. to 15 deg. as previously defined. However, depending upon the method of taking the temperatures, this allowance should vary over a considerable range, depending upon whether or not the method of measurement approximates the actual internal temperature. For instance, the total heat gradient from the inside copper to the outside air will be that through the coil insulation, plus the thick covering pad over the temperature bulb. If the gradient

through the covering pad is very large compared with that through the insulation, the thermometer may indicate almost exactly the internal temperature of the copper; that is, the heat gradient through the insulation to the thermometer may be relatively small compared with the total gradient to the air. This is particularly true where the thermometer rests on a metallic seat which covers a considerable portion of the coil surface. In this case, the heat which affects the thermometer bulb will pass through a relatively large section of surface, with a correspondingly small drop in temperature, so that the bulb more closely approximates the temperature of the inside copper.

Where there is local heating in the windings, and a consequent liability of rapid transference of heat to other parts, the results obtained by the thermometer method will vary to some extent with the rapidity with which the actual measurement is made; that is, the more quickly the thermometer can be brought up to the full temperature, the more accurately the temperature of the hottest part is determined. With a very rapid method of measurement, it may be possible to measure practically the internal temperature of the copper of the winding before any great heat transference or dissipation has occurred. In such cases, obviously, the full allowance for the usual temperature margin should not hold. It should be fully understood that it is the ultimate temperature, and not the temperature rise, which should be considered as the limiting condition, and that the measured rise, plus the allowances for temperature gradient, plus the measured room temperature, is simply an indication of the possible ultimate temperature. By whatever method the temperature measurement is made, in all cases the results may be considered as more or less approximate, and in the end, it is the manufacturer who must supply the necessary margin over the approximate measurement, in order to make the machine safe.

A blind adherence to some particular rule or method of taking temperatures may lead to fallacious results in some instances. In armature windings, in particular, incorrect readings may be obtained after shut-down. For example, if the armature iron back of the armature teeth were hotter than the armature teeth and coils during operation, then the temperature to which the insulation is subject during operation may be considerably lower than that in the hottest part of the machine, due to the ventilation conditions when running. However, upon shut-down, the

temperature at the insulation may rise to that of the hottest part of the machine, and therefore a false temperature, by any method of measurement, might be indicated.

Recommendations

That with class A insulation, 90 deg. cent. be taken as the ultimate temperature limit, as indicated by conventional methods of measurement, or those which give similar results, and that 100 deg. cent. be considered as the maximum ultimate temperature permissible in the insulation, where a comparatively long life is a requirement.

That 40 deg. cent. be taken as the limiting temperature of the cooling medium, or room, and that, therefore, 50 deg. cent. be the permissible rise by conventional methods of measurement, with class A insulation.

That 25 deg. cent. be taken as the reference air temperature. With the permissible 50 deg. cent. rise, this gives 75 deg. cent. as the average operating condition, by conventional methods of measurement, or 85 deg. cent. actual temperature, when the usual margin represented by the temperature gradient is added.

An exception to the rise of 50 deg. cent. can be made in those cases where space or weight limitations are such that higher temperatures, with consequent reduced life, are commercially economical, such as in railway motors. In such cases, with class A insulation, a rise of 65 deg. cent. with reference air at 25 deg cent. is at present accepted as good practise.

That with class B insulations, 125 deg. cent. be taken as the ultimate temperature limit, as indicated by conventional methods of measurement, or by equivalent methods, and 150 deg. cent. be considered as the maximum ultimate temperature permissible in the insulation. It follows therefore that 80 deg. cent. to 85 deg. cent. rise is allowable, with such insulations, by the usual methods of measurement.

No temperature correction should be made for variation of the cooling temperatures from the reference temperature of 25 deg. cent.

When the method of temperature measurement shows the highest temperature actually obtained in the insulation, the maximum temperatures specified for the given type of insulation should hold.

In the final decision on questions of temperature rise, the ultimate temperature should be the basis, rather than the rise.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

METHOD OF RATING ELECTRICAL APPARATUS

BY W. L. MERRILL, W. H. POWELL AND CHARLES ROBBINS

An investigation, covering the past three years, by the subcommittee on the subject of Rating Electrical Machinery, has shown conclusively that the present Standardization Rules of the American Institute of Electrical Engineers have, in many respects, become inconsistent as well as inadequate to meet the present service conditions which electrical apparatus is called upon to fulfill.

A comprehensive study of the subject has led us to believe that the rules representing fundamental methods of rating could be formulated. Such rules should not only meet existing conditions but also provide such flexibility as is necessary when limitations, due to existing materials, are changed by the future progress of the art.

It is highly desirable that the rating of electrical apparatus should be accurately defined and placed upon such a basis that it can be adopted internationally, since it is obvious that the service requirements in other countries are substantially the same as those in the United States.

This subject has been considered at great length by the International Electrotechnical Commission and an analysis of the work done by it leads us to believe that an international standard of rating is not only possible but essential. This is very desirable in view of the fact that the influence of the A. I. E. E. is recognized in the United States, Canada and Mexico.

The suggestions herewith submitted are based upon the accumulated data prepared after an analysis of service conditions, and represent the fundamental limits which should be considered in the rating of electrical apparatus, and it is believed

that further investigation and the discussions on service conditions will substantiate the conclusions herein presented.

Capacity Rating

Item 1. *All electrical apparatus should be rated by output.*

Item 2. *Apparatus which delivers electrical power*:

Apparatus of this class should be rated in kv-a., or in kw. where the kv-a. and kw. are equal:

a. Therefore, direct-current generating apparatus should be rated in kw.

b. Therefore, alternating-current generating apparatus should be rated in kv-a. at a definite power factor which must always be specified, if not inherent in the apparatus (as for instance is the case in the induction generator.)

Item 3. *Apparatus which transforms from electrical power to electrical power*:

Apparatus of this class should be rated in kv-a. or kw. in exactly the same manner as in item 2.

Item 4. *Apparatus transforming from electrical to both electrical and mechanical power*:

Apparatus of this class should be rated in kv-a. or kw., which represents the resultant of mechanical and electrical outputs, the two components being specified.

Item 5. *Apparatus which transforms electrical to mechanical power.*

Since the input in apparatus of this class is measured in electrical units, and the output has a direct relation thereto, it is logical and desirable to measure the delivered power in the same units. Therefore the output of motors should be rated in kilowatts.

On account of the predominant practise of rating mechanical power in h.p. it is suggested that apparatus of this class for the present be given a double rating, *i.e.*,

kw..... h.p.....

Service Ratings

An analysis of the service conditions that electrical apparatus is called upon to meet, leads us to recommend that ratings be divided into two general classifications, based upon the length of time of service the apparatus is in operation.

These two general classifications will again divide into three sub-classifications depending upon the character of the load conditions.

Continuous Rating. (A) In which, under specified conditions of operation, there is an attainment of approximately stationary temperatures, and no other limit of capacity is exceeded. This may be subdivided into the following classes:

(A 1) Constant service—where the load is continuously applied.

(A 2) Continued periodic service—in which the service consists of alternate conditions of load and rest, the periods of which must be specified.

(A 3) Continued pulsating service—in which the service consists of conditions of load and partial load, the magnitude and duration of which must be specified.

Short Time Rating. (B) In which, under specified conditions of operation, stationary temperature is not reached, and no other limit of capacity is exceeded.

(B 1) Short time constant—where the load is continuously applied for a specified period.

(B 2) Short time periodic—in which the service consists of alternate conditions of load and rest, the periods of which must be specified.

(B 3) Short time pulsating—in which the service consists of conditions of load and partial load, the magnitude and conditions of which must be specified.

Temperature of Electrical Apparatus

As the ultimate temperature is the sum of the temperature of the surrounding cooling medium and the rise of temperature due to the load conditions imposed upon the apparatus, it is necessary to take into account the variations encountered in the cooling medium. The cooling medium will vary in different places, depending upon geographical location of the apparatus, upon the season of the year, and the housing of the apparatus. Under this latter condition, it is found that the cooling medium may vary very widely in temperature, and may, in poorly ventilated places, and in locations influenced by other conditions, run as high as 40 deg. cent. even though the outdoor temperature may be lower.

It is believed that the average temperature of the cooling medium in which electrical apparatus is operated in practise and in which apparatus should be tested, is about 25 deg. cent.

It is therefore recommended that the standard temperature of the cooling medium be chosen as 25 deg. cent., and that all measurements and tests of electrical apparatus be based on a room temperature of 25 deg. cent.

Since, however, the life of the insulating material depends on the ultimate temperature attained, and this depends on the temperature of the cooling medium, it is necessary to recognize the

fact that apparatus is frequently operated in locations where the cooling medium may have a range of temperature much higher than 25 deg. cent. It is recommended that 40 deg. be recognized as the upper normal limit of the cooling medium and that temperatures higher than 40 deg. should be accepted as abnormal conditions that require special consideration.

Temperature of Apparatus

1. Ultimate Temperature:

A. Cotton, treated cloth, paper, and similar substances which may fall in this general classification, a maximum ultimate temperature of 90 deg. cent.

B. Heat resisting materials such as asbestos and mica compounds, etc., a maximum ultimate temperature of 125 deg. cent. Insulating material should be considered as belonging to class B even if containing material of class A, provided that class A material is used only as a means of facilitating construction and may be entirely destroyed without interfering with the functions of the insulation. In this case the ultimate temperature is that of class B.

C. Fireproof materials such as pure mica, porcelain, etc. No temperature limit can be specified.

These recommendations do not apply to apparatus, or parts thereof, the principal function of which is the generation of or dissipation of heat, (such as rheostats and heating devices) and to structures and materials which are not damaged by heat.

2. Temperature to be determined by approved method as may be specified in A. I. E. E. Rules.

3. Under the stipulated load conditions, the following temperature rises on windings are recommended:

CONTINUOUS SERVICE	
Class A insulation	50 deg.
Class B insulation	85 deg.
SHORT TIME SERVICE	
Class A insulation	55 deg.
Railway motors, class A insulation	65 deg.
Class B insulation	90 deg.

Short time temperature rises may be on a slightly higher basis, *i.e.* five deg. as indicated in the foregoing table, because the fluctuating load will permit of substantially the same life, in years, when operating intermittently under slightly higher temperature.

It is recognized that railway motors require special consideration, owing to the relatively larger power required in a confined space, and that therefore a higher temperature rise must be permitted, and that the life of the insulation under operating conditions will be materially less than for the other classes of service.

As railway motors operate under good conditions of external ventilation when carrying load, the temperature rise of 65 deg. is permissible.

Commutators. The heating of a commutator is due to several causes:

a. Conduction of current in the bars.
b. Conduction of heat from the armature structure.
c. Conduction of heat from the bearings.
d. Heating due to brush friction.
e. I^2R loss between the commutator and the brush.

This heating has no material effect upon the life of the insulation between the commutator bars, except that mechanical distortion may take place. The effect of the heating may, when excessive, cause deterioration of the commutator due to the distortion of the bars, but if the structure is so designed that *harmful* distortion cannot take place, the heating limits of the commutator should be that of the winding to which it is connected, *i.e.*, 50 deg. cent. for class A insulation; except in those instances where class A insulation may have a permissible rise of 55 or 65 deg.; or 85 or 90 deg. for class B insulation.

Other Material. The temperature rise of any part of the apparatus which is in contact with insulation must not be greater than that allowed for the insulation with which it comes in contact.

A higher temperature than that specified is permissible for such parts of the apparatus as do not come in contact with the insulation and therefore cannot, by their higher temperature, deteriorate the insulation.

Bearings. It is recommended that bearings should fall into the general classification of "Other Material" of the machine not in contact with insulation, and may have any temperature that will permit of safe and successful operation.

Service Ratings

It is recommended that continuously rated electrical apparatus falling within class (A 1) be rated upon a basis of ultimate temperature without other limits of capacity being exceeded, and

it is further recommended that no overloads be specified for apparatus except momentary overloads. Momentary overloads are defined as not exceeding sixty seconds, and should be as follows:

The maximum running torque of motors should not be less than 150 per cent normal rated torque.

Commutating apparatus should commutate not less than 150 per cent of the rated current.

Alternating-current machines should carry momentarily not less than 150 per cent rated current without regard to the rated voltage.

Motor-Generators. Generators should have the same overload requirements as designated under "Generators." The motor should have sufficient capacity and overload reserve to drive the generator.

Mechanical Service Conditions. All types of rotating machines should be so constructed that they will operate with safety at an overspeed of 25 per cent above the maximum rated speed, except in the case of steam turbines which, when equipped with emergency governors, should be constructed for 20 per cent over the maximum rated speed, and in the case of series motors no overspeed can be recommended on account of the varying service conditions.

Waterwheel generators should be constructed for the maximum runaway speed which can be reached by the combined unit under service conditions.

For a large percentage of apparatus which falls within classes (A 2) and (A 3,) and (B 1), (B 2) and (B 3), other limitations prevail. These types of electrical apparatus are designed to meet definite service conditions demanding selection of apparatus having a rating which will meet the exact operating specifications. These limitations are fundamental to the design, and it is therefore desirable that a definite commutation limit, a prescribed starting torque, a prescribed pull-out torque for a-c. motors, with a definite factor of safety for mechanical construction, be the limiting factors of the rating.

APPENDIX

Capacity Rating

Item 1. All electrical apparatus should be rated by output.

Item 2. In the case of alternating-current generators, the kilovolt-ampere is a much more logical unit than the kilowatt,

since the capacity of such machines when expressed in kilovolt-amperes is generally independent of the power factor, and in any case is much more nearly independent of power factor than when the rating is given in kilowatts. However, in the case of machines in which the field limits the capacity, the allowable kilovolt-ampere rating varies considerably with the power factor and hence power factor should be specified in all cases.

Item 3. In the case of stationary transformers, the rating in kilovolt-amperes is almost entirely independent of power factor, hence this method is the only logical one in this case. For synchronous converters, the rating depends both upon the power factor at the a-c. end and the direct-current load. Hence, both should be specified. For frequency changers and motor-generator sets, the same conditions obtain as in Item 2.

Item 4. Thus a synchronous converter which delivers both mechanical power and electrical power should be rated as kilowatt mechanical power and kilowatt (or kilovolt-ampere at a particular power factor) electrical output. If it is used partly as a synchronous condenser as well, for power factor correction, the a-c. power factor should be specified.

Synchronous condensers, for power factor correction only, should be rated in kilovolt-amperes at zero power factor. When a machine of this type is operating as a synchronous condenser, the power factor will not be quite zero, since losses are supplied electrically, but the difference will generally be too small to consider.

Item 5. From the pure science standpoint, the kilowatt is a better unit of power than the horse power since it is based directly upon the absolute c.g.s. system, the watt being equal to 10^7 dyne-centimeters per sec., while if we accept the definition of the horse power as being 550 ft-lb. per sec., it is a gravitational unit and so is not strictly constant, but varies slightly with the latitude.

Also the kilowatt is the practically universal unit for the measurement of electrical power throughout the civilized world, while the "horse power" beside varying on account of its being a gravitational unit is defined differently in different countries. In several European countries it is defined as 75 kg-m. per sec., while here it is 550 ft-lb. per sec. The difference is about 1½ per cent.

Then too there seems to be no real reason why both electrical and mechanical power should not be expressed in the same units,

and since the kilowatt is much more desirable as a universal unit than the horse power for the reasons enumerated, it is recommended that the output of motors be expressed in kilowatts instead of horse power.

In the case of synchronous motors which are also used for power factor correction, the power factor at the motor terminals should also be given (leading power factor being understood) unless otherwise specified.

Name-Plate Stamping

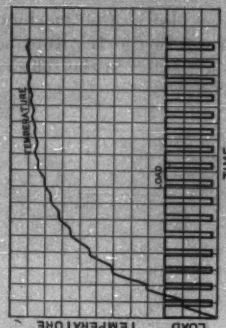
It is evident for ratings (A-2) and (A-3), (B-1), (B-2) and (B-3), that certain stand tests or compromise runs of machinery, and particularly motors, are desirable. These stand tests in addition to determining various characteristics of the apparatus, should also determine as a basis of comparison the heating of the machines, and as the machinery is selected for various and sundry cycles of operation, two methods can be recognized for stand tests.

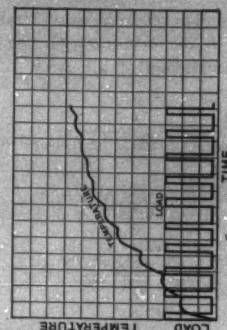
One is, in the case of class A machinery where the machine is run until it reaches a constant temperature under conditions where the losses and windage would be the same as the normal rating of the machine. This, however, in many cases might prove difficult, and a stand test made in accordance with a (B-1) rating could properly be substituted, as is now done in case of crane motors, machine tool motors, railway motors, etc., where the stand test may or may not be the same as the rating of the machine.

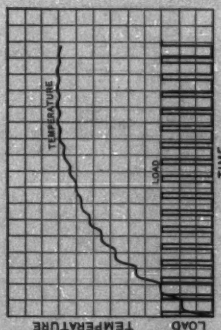
The present method of rating machinery on the so-called intermittent basis, is somewhat confusing, as for example; a motor rated "10 h.p.—two hours intermittent," really means that the motor will perform certain cycles of operation, the equivalent stand test of which is two hours of continuous running at 10 h.p. This is often interpreted to mean that the motor when installed will have to be shut down after two hours of operation or the motor will be injured.

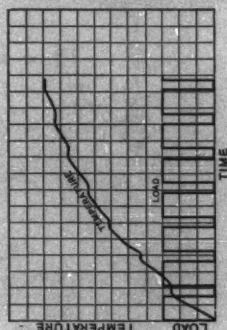
It is suggested that a system of name plate stamping be adopted which will designate the apparatus according to the various classifications set forth in this paper, and that in addition to the ordinary information given on the name plates, the equivalent stand test be included.

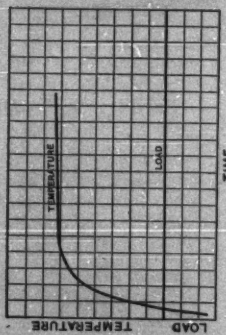
The following load and temperature curves indicate the nature of the six ratings as recommended by the sub-committee on rating.

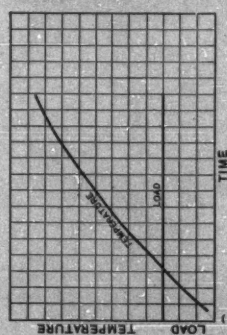

TEMPERATURE
LOAD
TIME
A3


TEMPERATURE
LOAD
TIME
B3

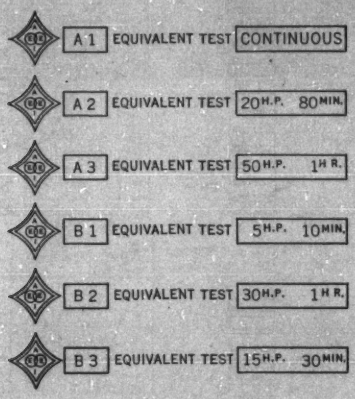

TEMPERATURE
LOAD
TIME
A2


TEMPERATURE
LOAD
TIME
B2


TEMPERATURE
LOAD
TIME
A1


TEMPERATURE
LOAD
TIME
B1

It is also recommended that the name plates of all machinery rated in accordance with the future rules of the Institute bear the inscription of the A. I. E. E., as suggested in the following examples.



DISCUSSION ON "TEMPERATURE AND ELECTRICAL INSULATION" (STEINMETZ AND LAMME) AND "METHOD OF RATING ELECTRICAL APPARATUS" (MERRILL, POWELL AND ROBBINS). NEW YORK, FEBRUARY 26, 1913.

F. B. Crocker (by letter): The paper on "Method of Rating Electrical Apparatus" by Messrs. Merrill, Powell and Robbins, Sub-committee on Rating, states that it is "recommended that no overloads be specified for apparatus except momentary overloads. Momentary overloads are defined as not exceeding 60 seconds" and are 150 per cent of normal rated torque or current.

This method is known as "Maximum Rating" or "Single Rating" in contradistinction to the present A. I. E. E. Standardization Rules, which require a definite overload capacity. In the case of a gas engine, maximum rating is not objectionable, in fact it is practically inevitable. Most electrical apparatus, however, is self-destructive as compared with a gas engine, which protects itself by stopping if its load is excessive. An electrical machine does not protect itself when overloaded; it exerts itself to carry increased loads until it reaches the point of self-destruction. The difference between electrical machinery and almost all other kinds is like the difference between children who want to study too hard and those who do not want to study enough. The former must be protected against themselves and require totally different treatment.

In practise it is impossible to predetermine the load of an electrical machine because it varies considerably and continually, with changes always taking place even when supposed to be constant. If a machine with no overload capacity is used to drive its rated load, the usual variations that occur are likely to be sufficient to injure it. If supplied with protective apparatus to safeguard it against overload, that same safeguard will prevent it from carrying the frequent and considerable variations in load occurring in practise. Those variations would make it necessary to adjust the safeguard at a point so much above the rating of the machine that it will be heated considerably beyond its normal temperature if it should carry, except momentarily, the load corresponding to this adjustment.

The basis assumed for maximum or single rating is briefly as follows: Fibrous (organic) insulating materials, as cotton, paper, etc., have a very long life provided that their ultimate temperatures never exceed 90 deg. cent. If, then, the temperature of the windings of a machine insulated with such a material does not exceed 90 deg. cent. when operating continuously, the maximum load at which it can so operate is taken as its rated load.

If, however, the machine has been running a sufficient time to bring its temperature up to 90 deg., any overload applied to it would heat the insulation beyond the safe temperature and

injure it. As already stated, no overloads are guaranteed on machines rated in this way. Beyond this point there is a disagreement between two groups of the advocates of single rating. One recommends that machines with such insulation should be rated to give an ultimate temperature at full load of 90 deg. The other group maintains that temperature rise, and not ultimate temperature, should be the basis for rating, so that a room temperature is assumed and deducted from 90 deg., the resulting temperature being the permissible rise.

The question is: What room temperature should be assumed? The temperature of ordinary rooms in which electrical machinery operates varies from 20 deg. to 40 deg. cent. The paper cited recommends "that 40 deg. be recognized as the upper normal limit of the cooling medium" or room temperature, which would make a standard of 50 deg. rise.

The ultimate temperature appears preferable because it eliminates the indefinite value of room temperature, but practically, the standardization of ultimate temperature would introduce confusion almost worse than no standard, because it would mean that before a sale could properly be made, investigation of the probable temperature of the customer's plant would be necessary and if one salesman estimated it at 25 deg. and another estimated it at 35 deg., the first would offer a generator for 65 deg. rise and the second salesman one for 55 deg. rise. The tendency would surely be to estimate the room temperature low, giving the customer as small a machine as possible, and endless trouble would result.

Moreover, any machine built in accordance with maximum rating must be applied to its work much more carefully than at present. Since it cannot carry any overload, it must never be overloaded, and therefore an intimate knowledge of the conditions under which each machine will have to operate, during its whole life, must be obtained. Even the most careful investigations can only go far enough to apply the motor properly in the first place, but they do not take care of future conditions. With single rating, a machine would have to be rated at the maximum load it would ever be required to carry, and who is the prophet to predict what that might be? It could not safely be depended upon to carry unexpected or even peak overloads higher than its normal rating.

For example, suppose a manufacturer buys a motor to drive a lathe and tests are made when the lathe is performing its regular work to determine the power required, the motor being selected and applied accordingly. If the manufacturer should obtain tool steel capable of taking a larger cut from the material in process, the single-rated motor would be incapable of securing the advantage of this new kind of steel.

Consider also a motor applied to a line shaft driving a number of tools. The manufacturer finds it advisable to add one more tool. If a motor of maximum rating has been chosen on the basis that its name implies, he cannot add the tool because of lack of

capacity in his motor, whereas the present type of motor would carry such added load without difficulty.

If the line shaft gets a little out of alignment, which is very likely to occur, a motor of maximum rating would be incapable of meeting this new condition.

It is argued that single rating is safe provided the temperature limit is put low enough. The machine would have a margin for overload, although none would be guaranteed. This would not be satisfactory to the manufacturer because he would not get and would not be entitled to any credit for extra capacity not guaranteed. Nor would it be satisfactory to the customer because he is not informed as to the danger point. If we have overload capacity in our machine, the customer will surely find it out and use it under unusual circumstances, hence we must inform him exactly what its limits are. If he is so informed, then we cease to have single rating and come around to practically the present basis of rating, which includes overload capacity.

Overload capacity is the margin corresponding to the *factor of safety* used in all branches of engineering. With maximum or single rating there is really no factor of safety at all. The two papers by the Sub-committees on Revision of Rules and Rating both clearly accept 90 deg. cent. as the maximum ultimate temperature, measured by thermometer. This is the actual physical limit and it is merely an arbitrary matter if we subdivide it and call it the sum of 40 deg. room temperature and 50 deg. cent. rise. The paper by the Sub-committee on Revision of Rules (on page 85 of this volume), allows for the fact that local spots or internal temperature will probably be about 100 deg. cent. at which the insulation defined above has "a comparatively long life." If, on the other hand, the maximum ultimate temperature of the *hottest* point does not exceed 90 deg. cent., then such insulation has "a very long life" (see page 81, line 1). Hence with the rating proposed, which permits 90 deg. ultimate maximum temperature measured by thermometer on the *surface*, the temperature will actually be 100 deg. in the *interior*, certainly in spots. At this temperature the life of such insulation is considerably shortened. The proposed limit is therefore 10 deg. above the true safety point, which is that point at which any considerable deterioration begins to occur. This point for electrical insulation corresponds closely to the elastic limit of structural materials. It is this limit and not the actual breaking point that is taken as the basis in allowing a factor of safety. The point at which the electrical insulation breaks down corresponds to the breaking point of structural materials.

The proposed rating not only fails to provide any margin or factor of safety whatever, but permits insulation be be used at a temperature at which it admittedly suffers permanent and considerable depreciation. Hence the margin is actually a ***negative***

quantity, and the factor of safety is less than one. Imagine a bridge that was "rated" in this way, its load being stated at more than its elastic limit. Of course with single rating this is the only figure mentioned, and most persons, either from ignorance, carelessness or something worse, would assume that to be what the bridge should actually carry.

An apparently good reason advanced for single rating is its simplicity. It sounds simple and therefore attractive, but it would be still simpler to have no standard at all. The purpose of a standard is to protect the public against ignorance and unscrupulousness, and the "single" standard would do neither. The purchaser would naturally assume that he could use a machine to carry the load at which it is rated. Certainly the seller would have every reason to allow him to think so. We are very far from the millennium when every customer will be so wise that he will correctly allow for a certain margin of capacity and when every salesman will conscientiously unbosom himself of all the limitations of the apparatus which he is endeavoring to sell.

As one who has always had a deep interest in the Standardization Rules of the Institute and who took part in their original formulation as well as both of their revisions, the writer firmly believes that electrical apparatus should not be single-rated. The manufacturer, the salesman, the purchaser and the user all need to be protected against their natural tendency, which is deep down in all of them, to take that rating as the proper actual load for the apparatus. Engineering is responsible for the introduction of proper factors of safety in the building of machines and structures. It is a violation of the fundamental principles of engineering and seems nothing short of foolhardy for electrical engineers to attempt to get along without factors of safety. Not only figuratively, but literally, it is Ajax defying the lightning!

James Burke: My understanding of the two papers is as follows: That the intention is to limit the ultimate temperature at which different kinds of insulation will be graded. The practise heretofore has been to have various temperature increases stated in the specifications. Some specifications are for 35 deg. increase, some for 40 deg. some for 50, some for 55, and some for higher increase. My understanding of the first paper is that independent of the increase in temperature, the paper intends to set an absolute limit so that if a temperature of the surrounding air is higher than 40 deg. the increase would be considered as a special case and set at a lower figure, and that the real intent of the paper is that it calls attention to the penalty of running at higher ultimate temperatures than specified in the paper. That determines the danger point from the user's standpoint.

Now, in order to apply that to commercial condition, it is necessary to agree upon a certain average of maximum air temperature for special purposes, and this paper suggests 40 deg. as the maximum which will permit of 50 deg. increase in tempera-

ture in machines with fibrous insulation as a standard commercial machine. As Mr. Lamme has pointed out, it is the ultimate temperature that determines the safety working point. But in the manufacture of machinery it is necessary to bring into consideration the increase in temperature, because on this condition the ratings of machines are determined.

I further understand that the intent of these papers is not to recommend that an increase of 50 deg. be standard, but that it be considered as a limit, so that if one wants to establish a lower temperature increase it is not inconsistent with this paper, it simply calls attention to the danger point, and that no temperature increases in excess of this should be considered good engineering practise, or should be recognized by the Institute.

On the suggestions of different ratings in the paper by Messrs. Merrill, Powell and Robins the intent seems to be to show six different kinds of ratings that may occur. The first is the continuous rating, which probably covers the majority of the machines today. That is classed as A 1, and then come five ratings that refer to highly specialized applications, not for motors that are usually sold under every day conditions, but in which the particular service has been carefully studied, the nature of the load, and the nature of the load variations, in order to employ entirely special motors for each instance. The A 2, A 3, B 1, B 2, B 3 have been suggested. My personal view is that they are suggested more for the purpose of bringing out discussion, although I am not posted on whether that is correct or not. The three A ratings relate to machines that reach an ultimate temperature. All the three curves show that the test is continued until a maximum temperature is reached. The A 1 is for a continuous load, constant load, the A 2 for a load that is on, and then entirely off for a period, and then on again, and then entirely off, and the A 3 for a load which varies between the maximum and minimum, and in which there is some load on all the time. The *B* ratings are in the same class as the *A* ratings, but for conditions in which the ultimate temperature is not reached, or, in other words, in which the service is such that the period of use is so short that the ultimate temperature is not reached, and that is the distinction between the two. I do not understand how it is to be determined what the equivalent test is. For continuous service, the equivalent test is a continuous test. For the A 2 class an 80 minute test is considered as an equivalent test, in getting the ultimate and final temperature for the service, which fluctuates between no-load and full load, or between out of service and in service. Now, that 80 minute test might be a proper equivalent for one condition of load, but it would certainly not be the equivalent for all A 2's. I would like to ask the authors of the paper to tell us how the temperature of equivalent tests would be determined for each kind of service.

The use of the initials of the Institute A. I. E. E. on the nameplates of machines, I think is intended to mean simply that the

temperature increase is not more than 50 deg., for fibrous insulation, and a higher temperature for other insulation, and also that the basis of rating is on the single rating or rating without overload, in other words the A. I. E. E. mark on the name-plate is a provision for 50 deg. increase and no overload. I do not think it is intended to mean that the A. I. E. E. approves of the A 2 rating being of the equivalent test of 20 minutes, or that there is any approval connected with that.

One very important point brought out in these papers is the matter of temperature correction, and I will say something on that subject after the papers on Temperature Correction are read.

Henry G. Stott: I wish to say one word in regard to the work of the Standards Committee. I think if you will review the past history of the Institute you will find that the present standing of the Institute work is largely due to the magnificent work and the unselfish support of the Standards Committee. I think it would be difficult to find a contract for electrical apparatus which has been drawn in the United States or in Canada in which you will not find the A. I. E. E. rules referred to as being part of that contract. I simply wish to convey my expression of appreciation to the Chairman and through him to the other members of the Standards Committee for the large amount of unselfish work they have done in helping along the Institute in this way.

Referring to the first paper by Dr. Steinmetz and Mr. Lamme, and coming to the curve Fig. 1, which applies to insulation of class A, I would say that the results shown in this curve do not conform to my experience with this class of insulation. I have had some rather bitter experiences covering some fairly large machines, and it is my experience that four years more nearly represents the life of insulation of this kind than ten years under the conditions outlined. In one plant the machines were 3500 kw. in size, operating at 6500 volts. The temperature rise on the average was about 40 deg. cent., and the surrounding air was 30 to 35 deg. cent., making an ultimate temperature of 75 deg. cent. The life of those machines has averaged very nearly four years, and as a result we have now changed the insulation from class A to class B, in the endeavor to get a longer life from the machines.

In regard to the second paper on Methods of Rating Electrical Apparatus, I would like to suggest, referring to the proposed name-plates on the last page, that where the letters "h.p." occur there should be substituted "kw.," and then within brackets after that, in very small letters, should be stamped h.p., so as to make the important thing the kilowatts and the unimportant thing the horse power.

Leo Schuler: I have listened with great pleasure to what Dr. Steinmetz said in regard to the new Standardization Rules, especially that it is the intention to adjust them to the standardization rules of other countries. It was of special interest to

learn that you intend to do away with the overload capacities, which was hitherto the main difference between your rules and the German rules.

You know that the International Electrotechnical Commission appointed a special committee for the rating or standardization of machinery, which committee had a meeting in Zurich in January, and the conclusions of the committee with regard to the admissible temperatures were about the same as are proposed in Dr. Steinmetz's and Mr. Lamme's paper. It was also decided to state, not the rise in temperature but the absolute temperature, as the life of the insulation depends primarily upon its temperature. The limit adopted in Zurich for class A (cotton, papers, etc.) was practically the same as proposed in the paper of Steinmetz and Lamme. That is, for impregnated cotton, we have stated that the temperature, if measured by the usual methods, should not be more than 90 deg. cent. For cotton, without impregnation, however, we have fixed the temperature at 80 deg. cent. only, because it seems quite certain that dry cotton without any impregnation will not stand mechanical stresses quite as well as impregnated cotton. However, for coils entirely impregnated with some compound so that all air is excluded, the heat conductivity is so much better than in an ordinary coil that the temperature gradient would be much less, and we therefore propose to adopt for such coils a temperature limit of 95 deg. cent. instead of 90 deg. This is, however, only proposed for continuous-current coils because in such coils the mechanical stresses are less than in coils for alternating current. The same limit should be adopted for coils which consist of only one layer of copper because necessarily the heat conductivity is much better than in ordinary coils, and the maximum temperature will be much nearer to the measured value.

Now, with regard to room temperatures, you propose to have a standard of 40 deg. cent. The International Commission has proposed 30 deg. cent. This is a great difference, of course. However, as is stated also in the paper by Steinmetz and Lamme, 40 deg. cent. will usually occur only in steam stations. Now, if we consider how many standard machines, especially motors, are used in ordinary rooms, and how many are used in steam stations—this will probably be one per cent or less—I do not think we should, therefore, introduce 40 deg. cent. as the normal air temperature for all standard machinery. Thirty deg. cent. will be quite sufficient, and even when in hot summer days 40 deg. occurs occasionally this would not have much influence on the life of the machine.

I should like to raise another question. If the curve Fig. 1 in Dr. Steinmetz's paper, for cotton in air, is assumed to be correct, there will be another somewhat lower curve for cotton in oil, as the deterioration of the cotton is due to the combined influence of heat and oxygen. We have in Germany estimated that the difference will be about 10 deg. cent., and, therefore, we

will allow 100 deg. cent. for oil transformers. Perhaps the authors of the paper will give their opinion on that point.

I should like to ask what the authors mean by "resultant temperature" when the cooling of the machine is affected by both the air temperature and another cooling medium, either air taken from outside, or water. Does it mean the mean temperature? That would not be correct, because it depends upon the distribution of the cooling effect on the air and the other cooling medium. In the new German rules the corresponding paragraph is as follows: "If besides the water or artificial air cooling considerable cooling takes place by the surrounding air, then the 'temperature of the surrounding' will be considered the temperature the machine or transformer attains when working not excited under the influence of the cooling medium." That means an additional test is made with the water turned on, under no load, and no excitation on the transformer, and then the final temperature is measured.

In regard to the second paper, I may mention that we use only the continuous "rating or rating for a certain time," that time to be stated on the name-plate; we do not speak of intermittent rating, intermittent service, or anything of that kind. I think that it is an unnecessary complication to adopt two temperature limits for continuous and intermittent service. This is simply a question of choosing the correct size of motor for the conditions of service. It will be understood that a motor for intermittent service will occasionally attain a higher temperature than it attains when tested under its rated load and within the rated time. It comes to the same result whether we use for a given service a motor of say 2 h.p. of one hour's rating with 50 deg. rise, or the same motor rated 20 h.p. for 90 min., with 60 deg. rise. I may further mention that we have in Germany tried to standardize also the time for rating machinery; we have adopted the rating of 10, 30, 60 and 90 min., which will probably meet all practical conditions.

W. L. Waters: Probably the most important statement in Messrs. Steinmetz and Lamme's paper is that "A blind adherence to some particular rule or method of taking temperatures may lead to fallacious results—and in the end it is the manufacturer who must supply the necessary margin over the approximate measurements, in order to make the machine safe." I think the committee would be ill advised to make, or to encourage the making of fixed rules at the present time for the measurement of internal temperatures in electrical machinery, as it is difficult even for the expert experimenters in the large manufacturing companies, who are giving their whole time to the work, to form an accurate idea of the distribution of temperature in a large machine.

Temperature tests are primarily to determine whether the insulation is operating at a dangerous temperature; but before this question becomes of any importance, it should be first

known that the design of insulation, method of manufacture, and workmanship, are satisfactory. It has been known for thirty years that mica was a very good insulator for high temperatures, when it was used under conditions where its lack of mechanical strength was no disadvantage. It was also known that asbestos could be operated satisfactorily at high temperatures, but its lack of mechanical strength and hygroscopic nature rendered it almost useless as an insulator. The progress that has been made is in the development of processes for utilizing these high temperature insulation materials so that their material weaknesses are overcome; and also in educating workmen to be capable of carrying out these processes. It should be definitely recognized that on these points, the purchaser is almost entirely dependent upon the manufacturer, and that rules are of no assistance in passing upon them.

I would suggest that at the present time, the Standards Committee should state that it is extremely difficult to obtain any exact idea of these internal temperatures, though the purchaser would do well to satisfy himself that the manufacturer has provided insulation suitable for operation at the temperatures which exist, and further that the method of applying the insulation and the workmanship are satisfactory. I think that some such statement as this would warn the purchaser or operating engineer of the danger which may be expected, and at the same time, will guard against the false feeling of security which frequently results after a few rough temperature tests have been made.

H. U. Hart: Those engaged in the design of generators of large capacity have known for a number of years that the temperatures in the middle of the core or coils were much higher than the temperatures indicated by thermometers placed on the outside of the iron or on the exposed portion of the coil. These interior temperatures have been measured by thermocouples or other means, and suitable insulation provided that will withstand the maximum temperatures.

The present rules of the A. I. E. E. for determining the temperatures on generators are inadequate, as they specify the temperatures to be taken by thermometers or by increase in resistance method of the windings. They make no mention of the maximum temperature allowable for the different types of insulation on the interior of the core of windings. Due to recent commercial development of a number of instruments to determine these maximum temperatures inside the slot, operating companies have been unduly alarmed by the temperatures obtained.

I have examined the armature coils on a large generator having class B insulation, which consists principally of mica insulation used in combination with other binding material. The coils had been in continuous service, operating at temperatures in the slot of approximately 110 deg. cent. for seven years, and there was no apparent deterioration.

We have recently developed an armature coil having no fibrous binding material, the coil containing only copper, mica and asbestos. This coil would probably come under class C insulation. Sample test coils were heated for several months in an oven at 250 deg. cent., and there was no apparent deterioration.

While it may not be advisable at the present time to work at such high temperatures, still it is interesting to note that suitable insulation can be provided, having such a wide margin over the temperatures recommended in the above paper. It would appear that instead of specifying very low temperature rises, necessitating a very expensive machine, there would really be more margin in a generator, having a fairly high temperature rise in the interior of the slot and fire-proof insulation.

I believe the recommendations of Messrs. Steinmetz and Lamme for the maximum temperature allowable on types A and B insulation to be conservative, and I would be in favor of having their recommendations incorporated in the Standardization Rules of the A. I. E. E.

B. A. Behrend: I want to say a few words about the history of the labors of the Standards Committee as I remember them during the last fifteen years. A report prepared by the former Standards Committee, of which I was a member for almost ten years, embodied rules with which we are all familiar, because they have been with us for half a score of years, or more. It is absolutely necessary in formulating a new code to consider the effect which the former code has had on the electrical industry, and I want to run over the past in a few minutes to present to you that aspect of standardization.

The old rules were conceived as expressing, as nearly as the art knew it at the time, viz., fifteen years ago, the facts known to the designers of electrical machinery. It represented partly the knowledge of the time, and partly the knowledge of the past. In fact, the code has always standardized the past. If there is any lesson at all in history, the new code is going to do the same again, viz., it will standardize the past. If we wish to standardize at all we have to standardize the past, for the obvious reason that we do not know the future, for which we should endeavor to cast our rules. With the constant progress and constant changing of conditions, there is nothing more dangerous than a rigid standardization, and while I want to express my own personal appreciation for the excellent work that has been done and which has been embodied in this large volume of papers, I cannot help but fear that the standardization report which is to be the outgrowth of so much valuable material will be a handicap again to the industry.

The old rules were of no assistance to the designing engineer, or the engineer in charge of manufacturing plants. They were mostly incomplete, misleading, and fallacious, and, with the authority of the A. I. E. E. impressed upon them, they have been

extremely harmful. No amount of facts presented could break the baneful influence of these fallacious rules. For many years I waged a campaign before this Institute in papers in which I presented voluminous experimental data, in order to demonstrate that the old rules as to regulation were useless, in fact thoroughly wrong and misleading. The method of measuring temperature by thermometer I contended was fallacious. But nothing could be done—the rules existed, handicapping the industry, the engineer, and the designer.

In the papers before us many of the old faults are corrected as we see them today, but let me ask you, will the new methods take care of the conditions as they will arise in the future? It is likely that, two or three years hence, these rules, by that time embodied in a code, will be a detriment again; may they not hamper again the designing engineers as well as the users of electrical apparatus? I fear that, if these rules are drawn too rigidly, with too keen a desire to embrace all the facts as we see them today, you will make a great mistake which it will be very difficult for you to correct in the future. Single ratings, or maximum ratings, are all right, but it is a new departure which is bound to cause much confusion until conditions have adjusted themselves to them. Our experience with the old code has shown that ten years after a rule has been advocated it has been adopted. Legislation follows the past, like standardization. I think we should endeavor to anticipate the future rather than legislate for past conditions, and that is, I believe, the weakness of the new Standardization Rules, for whose adoption I shall plead in a very general form, but, in fact, in so general a form as adopted by the German society. Such general form has the same advantage as the wonderful description of creation in the first and second chapters of Genesis. This story conceived probably thirty-five hundred years ago, has been worded in such beautifully general terms that it has fitted any theory of creation from the date of the Chaldeans to the evolutionists of modern times. The Book of Genesis is couched in such poetic, general language, that it can be applied to all conditions at all times. The report of the Standards Committee will be most sucessful if it also is couched in similar language, so that future generations will say, "these men anticipated our conditions."

James M. Smith: It appears that there are three standards to be considered. Two of them are adopted standards, the third a proposed standard. The first standard is that adopted by practise, and based on the experience of many years. The second is that adopted by the American Institute several years ago, but which has not been adopted by practise, and the third is the standard proposed in the paper by Messrs. Merrill, Powell and Robbins.

The standard of practise has a normal full load operating temperature that is conservative and safe even under severe conditions of operation or application. It permits overload

capacities which are stated, and are, therefore, a protection to both customer and manufacturer.

The American Institute standard which has not been adopted in practise requires the measurement of temperature by resistance which has not proved satisfactory, and allows for temperatures 10 deg. higher than that adopted by standard practise. The present proposed standard not only suggests temperatures 10 deg. higher than the present standard of practise but does away with all overload guarantee excepting one of maximum torque capacity which is stated to be 50 per cent above full load torque. It is apparent that the present proposed standard is for the purpose of making our guarantees similar to those of European manufacturers. This is for two reasons:

First, because it is considered desirable to have a world-wide standard, and

Second, to enable manufacturers in this country to compete successfully with foreign manufacturers in the export field.

For universal adoption, the first thing to consider is what are the correct standards. The present American standards are conservative and produce machinery ample in capacity to meet all conditions of ordinary service. European standards are not likewise conservative, and machines built in accordance with them must be carefully applied to avoid undue depreciation.

If the American standard is changed to conform with the European, then American purchasers educated in our conservative methods of rating will suffer from incorrect conceptions of the new rating until years have elapsed and they become educated to the new close margin standard. In determining standards of rating for electrical machinery the prime consideration must be the adoption of standards which will produce machines that will best serve the customer. It is my opinion that the European standards are not those which will best serve our American customers. It is also my opinion that the American standards will serve European customers better than the present European standards. Therefore, if a universal standard is to be adopted, I believe that standard should be the American and not the European, that is, the machine should have conservative temperature ratings at full load, moderate overload capacities, with safe temperature ratings and high maximum torques for the peak load conditions which almost every machine must take care of occasionally.

In the paper by Messrs. Merrill, Powell and Robbins the ultimate temperature is stated at 90 deg. In the paper by Messrs. Lamme and Steinmetz this is defined as being temperature measured either by thermometer or resistance, and it is recognized that the hot spot temperature may be 10 deg. higher, making the maximum temperature of the machine 100 to 105 deg., which by reference to the curves is above the charring point of fibrous insulation. Hence the machines are rated above the point of rapid deterioration, or, as stated by Prof. Crocker in

his discussion, they are rated above what corresponds to elastic limit and the breaking down point is only 50 per cent higher. I am strongly opposed to the new standard, or reduction of standard, for the following reasons: It would result in the purchaser receiving a smaller, lighter, and less powerful machine than before, with the sanction of the Institute.

Since these papers were issued I made tests on certain standard motors, both alternating-current and direct-current, which show that they could be increased in their rating from 15 per cent to 25 per cent and still meet the proposed new standards. Electrical apparatus is none too good, with a tendency to over-work it, and for many years an active effort has been made to raise standards, to fix them so that when the layman buys a 100-h.p. machine he gets a large and heavy one. The proposed change would result in his receiving a smaller and lighter machine.

Schuyler Skaats Wheeler: My interest in keeping up, or if possible, raising the standards for apparatus in this country is so great that I am impelled to say a word or two about one of the subjects before the meeting today.

I am an enthusiast about standards, and about the work of our Standards Committee. I think it is simpler, and therefore right, to use a single rating for motors and generators, provided this is done under proper conditions. But as I see it, the particular method of applying the single rating which has been proposed, incidentally has the effect of lowering the standard; this I am very much opposed to. Electrical apparatus needs plenty of margin or the adherence to a high standard; it is delicate and liable, unlike almost every other kind of apparatus, to approach the breaking point without the fact being visible to the user. The first thing he knows it is gone. For that reason alone, if for no other, it is desirable that it should have plenty of margin.

We are in the habit of producing electrical machinery in this country which, besides the power that it is said to be able to give, continuously, can give a much greater power for a short time. Therefore, its real capacity is a little greater than is represented to the customer. I think this reserve, or, as Prof. Crocker has said, factor of safety, should be preserved. I think it is very important to keep up the margins or factors of safety. I have been writing and talking on this subject for 25 years. My strong feeling on this subject really has nothing to do with the question of single rating by itself. I think it is perhaps a good idea to have a single rating, but let us provide a *lower temperature* for that single rating, as Prof. Crocker has suggested, so that the machine under the single rating for a given power has to be just as large as the machine furnished at the present time. This will entirely meet the objection that I have arisen to speak about.

I do not think we should in America make a smaller machine for a given power than we now do because the foreigners do. I think as Mr. Smith said, it would be better to try to induce the foreigners to come up to our standard.

I feel that this single standard will probably be put through, in any event, and, I do not think it worth while to make any great effort to stop it, as I think that would be useless. But I do want to go on record as to what my feeling is, so that later on I can call the attention of my friends to my position.

Philip Torchio (by letter): The main criticism of the two Sub-committees' reports is that the classifications by class *A* and class *B* insulation with their subdivision in class A-1, A-2, A-3, B-1, B-2 and B-3 is in my opinion too indefinite for every-day interpretation by the average user of apparatus.

The second criticism is that the service ratings recommended by the Committee are impractical for a great class of users of electrical machinery, like the central stations. I think that in this respect the Committee has taken too narrow a point of view of the practical service requirements in making the service ratings. To recommend that "electrical apparatus be rated upon a basis of ultimate temperature and that no overloads be specified except momentary overloads not exceeding sixty seconds" is absolutely impractical for a class of apparatus, like substation transformers, transformers on network, synchronous, converters, motor-generator sets, etc.

The systems of generation and distribution have up to the present been generally laid out on the basis of providing apparatus sufficient to carry the normal load with some overload capacity to take care of any occasional burn-out of a machine on the same bus or in immediate proximity on the distributing network.

All of this class of apparatus must have a liberal overload capacity for more than sixty seconds and at least one or two hours.

On the other hand, the apparatus that is limited in maximum output, like turbines, can be rated for a maximum temperature without overload capacity as recommended by the Committee. I think that this rating is a logical one because the apparatus is self-protected against excessive overloads and can therefore be safely rated for the maximum output.

On the other hand, apparatus that is not so inherently protected against overloads must logically be rated on a more conservative basis. To make a constructive criticism of what this basis should be, I would recommend that the Sub-committee on ratings be asked to prepare a comparative statement giving the corresponding capacities of a specific line of apparatus, like transformers, converters, motors, etc., giving the corresponding values of apparatus rated as at present with 35 deg. rise and 50 per cent overload for two or three hours, and the corresponding values of some apparatus on the new rating. By having this tabulated comparison one can then have a clear idea of what the recommendations of the Committee mean and so arrive at definite conclusions.

I am sorry that without this comparison between the present ratings and the recommended rating I cannot make an intelligent criticism of the new basis of standardization.

I would also recommend that additional information be submitted by the sub-committee on the Revision of Rules, giving the effect of vibration, moisture, etc. upon insulation as its reliability is not only dependent upon temperature but upon these other causes which should therefore be taken into consideration in arriving at the new standards.

Philip Torchio: I sent in a written communication in which I made criticism of these reports stating that the classifications of insulation, etc., are complicated and indefinite and that the single rating without overload is impractical except for apparatus that is inherently protected against overloads. I further pointed out that to make a constructive criticism of these reports they should be supplemented with a statement of how these recommendations compare with the present rating of machines.—In taking the above position in the matter I don't want it to be understood that I am opposed to the single rating, as I do favor it where it is practical. In fact the company I am connected with has been credited as having originated the single rating for turbo-generators, and I remember that in 1905 I wrote for my employers the first specifications for a single rating on turbines. This rating has since been quite generally adopted. In this instance the single rating is a logical one because the turbine is limited in its maximum output, and also its efficiency is good up to full output. When it comes, however, to transformers, synchronous converters, motor-generator sets, motors, etc., the same limitation does not hold true. For brevity I will not reiterate what has been said by previous speakers on this point.

You might say that the user can easily adjust himself to the new conditions by ordering large machines where overloads are required. However, I think that this would lead us into considerable misunderstandings and troubles. The present machines which have been built on specifications considerably more conservative than the present ratings of the A. I. E. E. have given and are giving considerable trouble. These troubles have been caused entirely by overheating in localized spots. There might have been a band that was put on to hold the windings of the armature which interfered with the proper ventilation, or there might have been faults of insulation, or the effect of moisture, dirt or vibration, or many other causes, but the fact stands out that machines running at probably 70 per cent of the proposed rating are giving trouble now.

We must give good service to users of electrical apparatus. It is to the interest of the entire electrical industry to do so. The central station, the manufacturer, the consulting engineer and everybody concerned with electricity is interested in giving good service.

I assume, as do some of the previous speakers, that the new specifications would make the machines smaller and not as liberal in design as the present rating. One of the previous speakers stated the contrary. If such is the case my argument

falls, but if machines are going to be smaller than they are now, I don't think we are justified in making such a departure. I recognize that the manufacturers have to meet competition in their export trade, but that is not for us to discuss. I would emphasize the necessity of consulting with the users and the central stations by submitting the problem to them in a more emphatic way than it has been done; perhaps by a circular letter asking their views and criticism. This matter should particularly be submitted to organizations like the National Electric Light Association, the Association of Edison Illuminating Companies and the Street Railway Association, forwarding to these bodies the Committee's reports supplemented by the additional information which I previously suggested, that is, giving a comparison in parallel columns the equivalent ratings of machines rated under the present standards and the proposed standards.

M. G. Lloyd: A fundamental question in discussing ratings is as to just what the word "rating" is taken to mean and what distinction is to be made between "rating" and "capacity." The capacity of a machine is limited by its ultimate temperature and this depends upon a number of conditions, such as room temperature, power factor (when this is determined by the load), wave form (when this is determined outside of the apparatus itself, as in the transformer), etc. It has been pointed out by the Committee that ratings should be based on the ultimate temperature as the limiting condition in the case of most electrical machinery, but just what distinction should be made between the capacity of the machine under working conditions and its rating? Capacity is a variable quantity determined by conditions. Should a rating also be variable, or should it be a fixed quantity for a given machine? This question is not clear in the Committee reports, especially in report No. 2. There seem to be several references to a determination of rating by the conditions under which the apparatus is to be used, and not by inherent factors of design and construction.

My own idea is that rating should be a fixed thing for a machine. The rating should be expressed for a definite voltage and definite frequency and should represent the load which may be carried under given limitations and certain definite conditions, and this quantity will not necessarily mean the capacity of the machine under any working conditions but only under some standard condition. For instance, a temperature rise of 50 degrees seems to be favored, based upon a room temperature of 40 degrees. Forty degrees is higher than the ordinary working temperatures. Nevertheless, in that case the Committee seems to have made the distinction that the rating shall be based upon a standard condition rather than the working condition. Elsewhere in the report, however, this distinction is not clear, as, for instance, in the case of power factor. Consider an alternating-current generator whose capacity, as expressed in volt-amperes, is not a constant, but varies slightly with the power

factor, due to the fact that you cannot always run the excitation up to the necessary point to get the same amperes from the machine that can be taken at high power factor. Should a machine of that kind be rated in terms of conditions under which it is to be used, or should it be rated in terms of a standard power factor? As to most of these points, like temperature and wave form, the implied meaning in the reports is to base the rating on standard conditions, but with regard to other features, like power factor, this does not seem to be the case.

Charles P. Steinmetz: I wish to state, first, that there is still some misapprehension regarding the purpose of this convention. The sub-committees have endeavored to gather all the information and data they could get together, but these are necessarily incomplete, and the convention was called, therefore, for the purpose of eliciting such additional data and information as may be available, and more particularly to reach those classes of engineers who could not be reached, due to the nature of things, by the members of the committee, and to obtain their ideas. The class of engineers referred to are, more particularly, the operating engineers and the consulting engineers. The designing engineers of the country, are grouped together, locally, in a number of centers, and therefore can be reached and have been reached, but the operating engineers as well as the consulting engineers are scattered all over the country, and their views and their experiences are just as important as those of the designing engineers, but it is more difficult to reach them, because, as a rule, they do not volunteer information, and there is no place where you can go and round up, to use that expression, a very large number of them, and therefore we anticipated by such a convention as this, by bringing the matter up for final discussion in the Institute, we would be able, at least to get a considerable number of operating and consulting engineers to give their views.

In regard to the question of temperature as the basis for rating, there are two misapprehensions. The first is to mistake single rating for maximum output rating. The single rating proposed is not necessarily maximum output rating, and, secondly, the single rating as proposed, is not necessarily a higher rating than the rating which was previously specified with our old capacity, but may be higher or lower, depending on conditions of apparatus. Now, what is the purpose of rating? An ideal specification is to say the apparatus shall operate for a long term of years without self-destruction. That is the ideal specification. In practise, however, certain reference conditions, must be definitely stipulated. The room temperature must be limited to a certain maximum, perhaps 40 deg. and the maximum insulation temperature must be limited to a definite value, 100 deg., or 150 deg., respectively, according to the class of insulation employed. Then the specification of the apparatus is that that apparatus should run indefinitely, and should give a good life, for any room temperature up to 40 deg., under any conditions of

operation where the maximum insulation temperature does not exceed 100 deg. cent. Now, you see that these two limitations immediately give you a definite power value. It is a definite value of output, which gives a maximum of 100 deg. cent rise in temperature at a maximum of 40 deg. temperature in room. Under any other condition you can take more power out of the apparatus or less power. What we propose then is, as single rating, to give the rating which the apparatus would have and the maximum output which it can carry at a room temperature not to exceed 40 deg., and with an insulation temperature not rising above 100 deg.

Now then, if you operate that apparatus at a lower room temperature than 40 deg. you can get a larger output. If you operate the apparatus for a short time only at 40 deg. room temperature, you can get a larger output, for time and temperature in insulation, as in many other things, are interchangeable.—It is not true without further qualification, to state that cellulose fibre carbonizes at 100 deg. cent., or 120 deg. cent. The carbonization temperature of self-destruction is a function of time, and the shorter time allows higher temperature. Now you will understand that what the present proposed single rating means is this; it gives a maximum of output which the apparatus can carry continuously at any room temperature up to 40 deg.

Let us compare that with the previous specification of the rating and overload margin. Under that specification you were no better off; the intended margin was not sufficiently definite. When buying a machine at the old rating, *i.e.*, at a certain rating with a certain overload guarantee, you knew much less what you could get from the machine than you will under the single rating. It has been said that the machine should have a safe margin of 25 per cent in output. That means, that if you know the machine must carry a certain load, you will buy a machine rated at that load. On the old basis you would buy a machine capable of carrying a 25 per cent greater load. If it should happen that the load is steady and you never have any overload, you merely have thrown away 25 per cent of the output of the machine, and have spent more money for the machine than was necessary. You have bought a larger machine than was necessary. If it should happen that the average load, equal to the rated load, should fluctuate up or down 10 per cent, then you still have an unnecessary margin of 15 per cent. If it should happen that your load varies 50 or 100 per cent, it means that your margin of 25 per cent is worthless and your machine will burn out. The margin means nothing, and you cannot say that you will buy a machine for that rated load and that it will be safe. What you must do when using the old rating is to say that the machine has a certain rating and has 25 per cent overload capacity. The maximum output required of it is a certain known value. The maximum output the machine can carry, is 25 per cent overload, and this is what you require the machine to carry. From this you must

deduct 25 per cent in order to arrive at the normal rating of the machine which you require for your purpose. You can simplify things by leaving out that 25 per cent overload, which is not overload, and merely say the maximum output of the machine is so much, or your maximum load is so much, and therefore, you buy a machine rated at whatever you have to carry. You see that there is no difference in the one way of rating or the other one, with the exception that in the old way the Institute established 25 per cent overload as the average satisfactory margin. But wherever you do not need the margin you get too large a machine. Where you need a larger margin, as in the machines to which Mr. Torchio referred, the machines complained of, you burn out the machines, and the Institute rules are of no value. The new proposition is to throw on the customer the burden of determining the appropriate overload capacity to be provided in each case. At the present time the industry is far enough advanced for the operating engineer to know enough to select his own margin, to know that he must allow no margin in such a case as the steam turbine driven alternator, and that he must allow 50 per cent or 100 per cent margin or even more, in such cases as synchronous motors operating in substations. By the new method the purchaser can get a machine to suit the conditions of each case. This was not the case where we had a rating and allowed a standard uniform overload.

We propose to bring up here for discussion the proposition to go a step further than heretofore and merely give a single rating, and then say that from this single rating you have to subtract whatever margin your particular requirement may need, to arrive at the size of the machine adapted to the diversified conditions of the industry.

Henry G. Reist: I want to point out that probably we have become accustomed to rating machinery with large overloads, due to the long experience with the steam engine. A reciprocating steam engine always had large overload capacity. On the other hand, the gas engine, and the waterwheel, and now the steam turbine, are rated practically at the maximum load. There is a reason for this. The steam engine works with the greatest economy at about the point at which it is rated. The overload capacity is not put there for possible overloads which might come on unexpectedly, but it is rated at the point where it gives the highest efficiency. The same holds true with the waterwheel, the gas engine and the steam turbine, they rate them at the points where they give approximately the best efficiency. We should rate electric motors so that they will have the best average efficiency. At the present time many electric motors are shamefully underloaded. Running them at an underload means that the customer pays more for his motor than he should pay, he has lower average efficiency, and with an induction motor lower power factor, which means a more expensive transmission line, greater losses on the line, and bigger machines on the other end. We had a definition given us this morn-

ing of what an engineer ought to be, or ought to do, and I might point out that one of the duties of an engineer is to get the most use out of a given amount of material and expense.

The reason, probably, why motors are used underloaded is because the customer hesitates to put a greater load on them than is designated on the name-plate. If his work requires 40 h.p. he will probably say, "I will make it safe, and get a 50-h.p. motor," and he will run it all the rest of his life at 40 h.p., and probably under that, and consequently he has poor efficiency and all the things I have just pointed out.

I was very much interested in the proposed ratings for motors, that is, continuous and various intermittent ratings. It occurs to me that the schedule proposed is rather complicated, and I like much better the one that, as suggested, has been adopted by the German engineers, simply giving the rating, based on a run of a certain length of time; that is, it might be 10 min. and 30, 60, 90, as has been adopted by the German societies, or it might be some uniform increase, which I would like a little better, such as, for instance, 10, 20, 30, 40, and double that, or equal values geometrically, between the length of time under which they are operated. From each of these ratings the consulting engineer can select the one that is most suited for his work, after he has definitely determined, as nearly as possible, what the work to be done is. It also seems to me then instead of giving them arbitrary letters and numbers as A 1 and A 2, and B 1 and B 2, they might simply use the length of time that the motor runs at its rated load as the name by which to know this particular rating. That would somewhat simplify the nomenclature, I think.

I just want to say one other word about the first paper, regarding the recommendation that we consider ultimate temperatures rather than rises. I must confess I am a little stupid on that point and do not quite see the difference, because it seems to me that, if we use an ultimate temperature, we must take some room temperature as a standard, and it is suggested that this be 40 deg., with which I entirely agree, and that the rise on top of that, which is recommended, is 50 deg., I believe, which, after all is a rise of 50 deg. I agree with Dr. Wheeler and several other gentlemen who have argued for conservatism. I question the advantage of going to too high temperatures in most cases. There are exceptions, such as in the case of the railway motor, and probably in a good many other cases, but when it is not necessary, let us keep to low temperatures. The difference in cost of construction between the two machines is comparatively slight, whether we keep a little lower temperature or go to higher temperatures; and then, if you use mica or other material for external insulation, there is always the insulation between turns which becomes particularly difficult with the smaller apparatus, where it is difficult to put mica around each small wire of which the coil is composed. If the coil consists of a few conductors

they may be taken care of, but when you have twenty to thirty, as we have in many cases, it becomes very difficult, and to me the only solution at the present time is to keep the temperature down. Some time we shall probably find insulations that will stand higher temperatures, but I do not feel that we have them for general use at the present time.

B. G. Lamme: I shall not undertake to discuss the arguments brought forward, but I wish to bring out more fully some points which seem to be very much misunderstood. There seems to be, in general, a wrong impression about the limiting temperatures which have been proposed, as some of the members appear to think that we are advocating raising the present temperature limits. On the contrary, we are proposing to cut them down. It is apparently believed that in adopting a temperature rise of 50 deg. cent. that we are insisting that apparatus be built for that temperature. However, what we actually said was that the temperature rise shall not exceed 50 deg. measured either by thermometer or resistance, *whichever gives the higher result.* We can keep as far below 50 as we please, depending upon what margin we wish to allow. We simply say that 50 deg. cent. rise shall not be exceeded, and that with the limiting air temperature of 40 deg. cent. the ultimate temperature of 100 deg. cent. in the hottest part shall not be exceeded. It should be understood, however, although it is not brought out sufficiently clearly in the committee papers, that the 10 deg. difference between the measureable temperature and the actual hottest part should apply only to ordinary low-voltage insulations, such as 2200 volts and less. For relatively high voltages, with correspondingly thick insulations, a greater difference than 10 deg. cent. must be allowed between these temperatures.

In the present Institute rules, 50 deg. cent. rise by resistance is allowed, and on top of this, an overload of 15 deg. higher is allowed, giving a total permissible rise by resistance of 65 deg. cent. We claim that that is unsafe, except in those cases where the cooling air temperature is not over 25 deg. cent., for 65 deg. + 25 + 10 deg. internal drop = 100 deg. ultimate, which is the limit of safety. But taking air temperatures of 40 deg. cent., then 65 deg. + 40 deg. + 10 deg = 115 deg. ultimate, which we contend is unsafe. Therefore, we propose to cut out any conditions of the load which will put the ultimate temperature above 100 deg. cent. However, it must be understood that temperatures above 100 deg. cent. simply shorten the life of the apparatus, and do not mean immediate destruction. This shortening of the life, in most cases, does not show up during the overload condition, as this usually represents but a small portion of the total operating period. The carbonization of the insulation, however, usually occurs on the peak load, and not under the normal operation. We therefore propose to cut out those conditions of temperature which are liable to have a material effect in shortening the life of the apparatus.

It has been mentioned several times that it is a maximum rating that we are proposing, and it is claimed that the proposed single rating and maximum rating are the same thing. However, it is not our intention to adopt a true maximum rating. I can possibly illustrate the difference by an example:

Assume a cooling air temperature of 40 deg. cent. and a rise on top of that of 50 deg. cent. and an internal temperature difference of 10 deg., giving 100 deg. ultimate. That fixes the limiting rating possible without exceeding the ultimate limit. This we call the single rating. But with cooling air at zero, with this single rating we still retain the 50 deg. rise, so that the ultimate temperatures becomes 60 deg., and not 100 deg. However, under this same condition, the machine could have a maximum rating corresponding to 90 deg. cent, rise instead of 50 deg., or the maximum rating, with air at zero, would be 80 per cent greater than the single rating which we are proposing. A machine could have all kinds of *maximum* ratings, depending upon the air conditions, whereas, they can have only one *single* rating, which is fixed in value by the conditions of air at 40 deg. cent. It seems to me that this confusion of the proposed single rating with maximum rating is back of much of the misunderstanding of the subject which has been expressed here this morning.

As the present Institute rules allow 50 deg. cent. rise under normal conditions, with 15 deg. higher temperature for overloads, and as the new method proposes 50 deg. rise as the highest permissible, it is obvious that, in fact, the machine, under this new method of rating could actually carry as much overload as under the old method, the only difference being that, under the new method, we recognize the danger in this overload, and call attention to it, and recommend against it, while in the old method, we went ahead and blindly guaranteed it. The new rules indicate a definite danger point, while the old rules did not. That is the principal difference between them.

Alexander Gray: In regard to the two papers presented this morning, there are several points about which I do not agree with the writers.

Much attention has been paid to the apparent fact that the limit of a machine is the temperature rise of the insulation. This may not always be the case, because the ordinary iron which we use is not non-aging iron. There is non-aging iron on the market, iron in which the losses are small and do not increase with time, but that iron at present is rarely used for revolving machinery, because it is found that the losses are not reduced as much as would be expected, and also that such iron is liable to crack when subjected to long-continued vibration; it is well known that the long teeth of induction motors, when made with this iron, sometimes break off and damage the windings.

Regarding the temperature limit of 90 deg. which is suggested for class A insulation, I consider it to be too high. Present practise calls for a temperature rise of 35 deg. cent. on full load,

and 50 deg. cent. on 25 per cent overload, for two hours. Now, it is well known that 25 per cent overload at two hours on the top of a full load run is equivalent to 25 per cent overload continuously; that is to say, our present motors will carry 25 per cent overload continuously, with 50 deg. cent. rise, and will not deteriorate rapidly, but few designers would care to guarantee 50 deg. cent. rise, measured by conventional methods, when the motor is known to operate in a room with an air temperature of 40 deg. cent. I should suggest that, with class A insulation, the upper limit, measured by conventional methods, should be put at 80 deg. instead of 90 deg. cent.

In discussing the second paper, the first point I would draw attention to is that all alternators should be rated in kv-a. and not in kw., even although the power factor be 100 per cent. There is a great deal of misunderstanding on this point at present. The Institute rules which we now have, state that a machine of 100 kw. output and 80 per cent power factor is a 100-kv-a. machine, whereas in practise such a machine would have a rating of 100 kw., but would have a kv-a. rating of 125. This point should be emphasized and made very clear in the new rules.

With regard to the rating of machines, we have, at present, continuous ratings, intermittent ratings, and short time ratings. Our Sub-committee on Rating suggests that this classification has not been carried out in sufficient detail, and now proposes to divide machines into two main classes, and six subdivisions in all. The large bulk of electrical apparatus is built for continuous duty, it being remembered that most machines, and particularly the copper in the machines, reach their final temperature in about two hours. That being the case, we have a comparatively small number of machines which are operating for less than two hours continuously, and these, it is proposed, shall be subdivided into five sub-classes. I consider that this matter has been carried too far and will lead to endless difficulty. I have asked several engineers in what class they would put a railway motor. Many of them said under the heading A 2, others, again, would put them in class B 2. We can think of many other cases in which it would be exceedingly difficult to put the motor in its proper class.

In considering what I would suggest to take the place of these five classes, I looked over a paper published in the *Journal* of the Institution of Electrical Engineers, by Dr. Pohl, and he suggests that for intermittent ratings an intermittency factor should be used: an intermittency factor of $\frac{1}{6}$ means that out of every six minutes the motor would be operating for one minute, and would be stationary for five minutes; a large number of applications, such as crane service, have perfectly definite intermittency factors. Now, a 50-h.p. motor with an intermittency factor of $\frac{1}{6}$ would operate at 50-h.p. for one minute out of every six and have an overload torque corresponding to a 50-h.p. machine, but if this machine be rated at 50 h.p. for half an hour,

or at 100 h.p. for ten minutes, or at 40 h.p. continuously, what connection is there between the horse power rating and the overload capacity? The new suggestions are far from clear on this point.

With regard to bearings, considering that a large number of electrical machines, motors in particular, are in the hands of inexperienced operators, I do not believe it advisable for the Institute to recommend that bearings should fall into the general class of other materials, and have any temperature which will permit of safe and successful operation. Just as we specify temperatures in insulation, because the material gives no indication as to when it is going to break down, so in high-speed bearings, where there is no indication given that the bearing will seize, it is advisable in the interests of the public, who in the case of bearing breakdowns, will be charged with the use of poor oil, to limit the temperature of the oil in the bearings to 70 deg. cent., unless otherwise specified in some binding specification.

It must be remembered, finally, that it is not always the final temperature which limits a machine. The mechanical parts are built to suit a certain temperature rise, and if machines are designed for an air temperature of 40 deg. cent., then they will have considerable overload capacity with an air temperature of 25 deg. cent., but this overload capacity is not available unless the mechanical parts are sufficiently strong.

R. F. Schuchardt: In general I believe in a single rating, provided it is the continuous rating, and represents a safe margin. The other five ratings proposed in the paper of Messrs. Merrill, Powell and Robbins are undesirable for several reasons. First, we would have a number of different ratings for the identical motor, which means in a central station for instance we would have to carry a large storeroom full of spares where otherwise a few would do, and the number of motors to be carried in stock would be multiplied greatly. The continuous ratings should also be given if it is desired to have any of these special ratings. Second, the proposed ratings would complicate rate-making, which is already a pretty complicated matter. The basis generally adopted for power rates contains a primary charge for the maximum demand. In motor installations the primary charge is usually based on the rated capacity of the motors. Now you can imagine what complications would be introduced in rate making by such a multiplicity of special motor ratings.

I do not agree with a preceding speaker regarding the use of the Institute symbol on name-plates. It would be a very grave error to put this symbol on apparatus, as it would be generally interpreted as putting the stamp of approval of the A. I. E. E. on the apparatus which bears the symbol.

There are two minor points which should be changed. In the paper by Messrs. Merrill, Powell and Robbins the statement is made: "Commutating apparatus should commutate not less than 150 per cent of the rated current." In railway machinery this should be "not less than 200 per cent."

In a succeeding paragraph the following statement is made: "All types of rotating machines should be so constructed that they will operate with safety at an overspeed of 25 per cent above the maximum rated speed." Synchronous converters, particularly, run away very fast, and the speed may increase at a tremendous rate, so that should read considerably higher than 25 per cent for the safe speed limit.

One word more, on the much discussed point of ultimate temperature. About five years ago we had an experience in a large central station in the West, during which we burned up a very large generator, and as a result of that we made some detailed investigations of the safe temperature limits for the insulation used on this particular class of apparatus. After we had carefully studied all of the test results we finally decided that 80 deg. is the maximum safe point below the knee of the heating curve which should be allowed, and that point determined by means of an exploring coil laid along side of the armature coils in the machine.

The paper of Messrs. Steinmetz and Lamme recognized the fact that there may be hot spots as much as 10 deg. higher than the measured temperature. We also assume that there might be hot spots even above this exploring coil measurement but we do not feel that it is safe to work on so close a margin as recommended in these papers.

C. E. Skinner: We have all been familiar for quite a while with the fact that the life of insulating material is a function of time, temperature and the mechanical conditions under which it is used. We have endeavored for a long time to find what is the ultimate upper temperature to which different classes of insulating material can be operated without getting into trouble. The German standardization of 80 deg. for cotton insulating material has been referred to. It is very rare, at this time, to find windings of electrical apparatus which are not treated in some way so as to bring them into the 90 deg. class as outlined by the Standards Committee.

J. M. Smith: There is one point which is not at all clear to me. It has been stated this morning that 90 deg. ultimate temperature was the hottest temperature in the machine. Mr. Lamme, both in his paper and his statement this afternoon recognizes that the hottest spot in a machine may be 10 deg. or 15 deg. higher than the ultimate temperature. This can be seen by reference to his paper. The difference between these two points of ultimate temperature is a difference of 10 deg. in the temperature rise, and it is the difference of between 15 per cent and 25 per cent in the capacity of the machine. I would very much like to have this important point cleared up.

B. G. Lamme: I wish to explain one little point wherein there seems to be some misunderstanding. It has been stated in the paper on "Temperature and Insulation" that a limit of 100 deg. to 105 deg. was allowed for fibrous insulations. I do not find

any place where 105 deg. is either mentioned or indicated. Ten deg. to 15 deg. is mentioned as the possible internal drop, but the 15 deg. is tied up to 85 deg. This higher internal drop referred simply to cases where there was heavier insulation than in the ordinary moderate voltage machines. It was not brought out plainly enough in the paper that with very high voltage machines the internal drops should be considerably higher than indicated, possibly 20 deg. to 25 deg. Where 25 deg. internal drop is liable to be found, then, with fibrous insulations, 75 deg. measurable temperature would be the limit, and not 90 deg. It should always be borne in mind that where the ultimate temperature limit is fixed, the internal drop must be subtracted from this to give the measurable temperature, and this may be 90 deg. in some cases, while in other cases it may be 80 deg., or even 75 deg. depending upon the type of apparatus.

James Burke: If there is one point of more importance than another that has been brought out in these papers, I think it is the viewpoint which has been put on record that we have to recognize hot spots rather than any other temperature condition. I think a great deal of the discussion has been brought about due to the difference between the two papers. According to one paper, we can rate machines higher, according to the other we would have to rate them lower. So if we are discussing the paper of Dr. Steinmetz and Mr. Lamme, we can come to the conclusion that we may rate machines higher than the present commercial practise. If we discuss the paper by Messrs. Merrill, Powell and Robbins, we are in the class of conservatism which has been advocated by so many speakers here and previously.

In the paper by Dr. Steinmetz and Mr. Lamme they call attention to the fact that with fibrous insulation 100 deg. should be the maximum temperature, and then they assume 10 deg. for the difference between the maximum hot spot and the conventional measured temperature, and then come to the conclusion, when you measure temperatures by conventional methods, quoting their words, as follows: "The conventional methods of temperature measurement, as by resistance and by thermometer, do not usually give the maximum temperature, but give either the average or the outside surface values, and, when measuring the temperature by these methods, which are the only ones generally applicable, an allowance must be made in windings for possible local higher temperatures." Now, if we consider that the 100 deg. hot spot recognized in that paper allows 10 deg. for some temperature gradient, leaving 90 deg. ultimate by conventional methods, with an air temperature of 40 deg., we have 50 deg. increase by conventional methods. That is the same as the existing rule of the Institute that has been in force for several years. It is not, however, in line with what the commercial practise has been. The commercial practise has been 40 deg. or in some cases 45 deg., so that if we compare the present commercial practise of 40 deg. with this pro-

posed 50 deg., we can rate our machines up, as Mr. Smith pointed out, from 15 to 25 per cent. I have made some similar tests and have found about the same conclusions. This comes from raising up the magnetic densities 12 per cent and the copper densities 12 per cent, and 12 per cent increase in current means approximately 25 per cent increase in copper loss and 25 per cent higher temperature, making a difference of from 40 to 50 deg. On that basis, if it is interpreted in that manner, we can rate machines up, and we are getting away from the direction of conservatism; but if we take the other paper, by Merrill, Powell and Robbins, we find that they advocate a maximum temperature of 90 deg. They say under the heading of "Temperature of Apparatus," as to ultimate temperature, the following, "a. Cotton, treated cloth, paper and similar substances which may fall in this general classification, a maximum ultimate temperature of 90 deg. cent." They evidently mean the hot spot temperature. The next thing is, how are we to determine that hot spot temperature. They do not say how it is to be determined, but they do say, "Temperature to be determined by approved method as may be specified in A. I. E. E. Rules." Now, then, the whole issue regarding temperature comes into that paragraph of what the A. I. E. E. Rules will be for determining the temperature. If the Institute Rules adopt a method that really gives the hot spot temperature, we will have lower conventional method temperatures than heretofore and more conservative.

We have among the papers to be presented at this convention one by Mr. R. B. Williamson, who shows one method of calculating the hot spots or the difference between the temperature of the laminations and the temperature of the surface of the coil, and he shows two tests, one his own, presumably with 19.5 deg. temperature gradient from the insulation, and quotes the test of some one else who shows 20.60 deg. In addition to that temperature gradient, there is another one from the outside of the coil to the inside of the coil, that is especially so if the coil is made up with round wires, with cotton insulation and air space between. So that with this temperature gradient assumed at 5 deg. added to Williamson's 20 deg., we would have 25 deg. of temperature to start with. That leaves us in the case of 100 deg. ultimate temperature, 75 deg. measured by the conventional methods, and deducting 40 deg. leaves 35 deg. increase.

This whole question of whether we are going to rate machinery up or rate it down depends entirely on what the Institute adopts in connection with this clause, "Temperature to be determined by approved method as may be specified in A. I. E. E. Rules." If we adopt the conventional 10 deg. temperature gradient, we are making a compromise. If we adopt a method of tabulating and calculating it for different thicknesses of insulating wall and different conditions, we are getting down to a more conservative rating. Difference of opinion seems to be on this point, and I think it will be determined one way or the other, depending on

how these temperatures are to be determined. If the Institute adopts consistent rules for determining that temperature gradient to the inner part of the coil, the recommendations will be more conservative, and they will lead to the adoption of lower temperatures measured by conventional methods. I think if these few points are kept in mind we can come to a complete understanding, and find that every one is in accord on this subject of temperature. I think the sentiment of everybody is in the direction of more conservatism.

Charles P. Steinmetz: I wish to say that in both papers, in referring to the 90 deg. ultimate temperature, it is understood to refer to the temperature measured by thermometer or resistance. That is the average outside temperature, and not the temperature of hot spots which may be 10 deg. higher. Both papers recognize as the limiting permissible temperature rise, under extreme conditions, 50 deg. cent. Therefore, both are equally conservative or equally unconservative. However, I wish to draw your attention to one misunderstanding. There seems to be some idea that the new rule is less conservative in allowing 50 deg. temperature rise than was the former rule. As a matter of fact, it is more conservative, because the former A. I. E. E. specification allowed in electrical apparatus 50 deg. rise of temperature at rated loads, and in addition allowed 15 deg. more, or 65 deg. rise, at certain overloads for limited times. Now, in the new rules we do not permit the additional rise of 15 deg., because 65 deg. rise is not safe for all insulations and under all conditions. If the room temperature is 25 deg. cent., then you can have the additional 15 deg. rise, and still not exceed safe temperature limits even for class *A* insulation. If your room temperature is 40 deg. cent., you cannot permit 65 deg. rise, as determined by conventional methods, without exceeding safety limits for class *A* insulation. The only change which has been made from the old rules is that of leaving 50 deg. rise as the maximum standard rise. We no longer allow that additional 15 deg. Thus you see, we have really cut down the permissible excess rise above 50 deg., leaving, however, the 50 deg. as the standard which was recognized before.

I want to take issue with one statement, that 50 deg. was the *Institute* standard, but the *universal* standard was 40 deg. When we consider these lower temperatures, we always think of the big, the important apparatus, the special high class machinery. That is all right, if we say that 50 deg. is the maximum permissible guaranteed rise, that does not exclude lower values but rather makes it desirable for us in this class of machines where we want to have extra-safe apparatus, and where we have big machines on which we can afford to spend some money to get good service conditions. There is no change from 40 deg. to 50 deg. Fifty deg. was the maximum permissible temperature. Thirty-five to 40 deg. may be specified and has been specified very largely, and will be specified in the future to suit special

conditions, but there is a large mass of apparatus in which 50 deg. has been and is industrially used, and even higher temperatures, which we have to avoid and discriminate against. But the large mass of apparatus being built to-day, and which has been built in the past, has a 50-deg. rise, and we never think of it, because such small apparatus goes out in wholesale quantities. It is often put out by the smaller manufacturers and is good enough at 50-deg. rise, as good as is usually required. We have to recognize that this apparatus which is being manufactured wholesale is giving satisfactory service, and we cannot prescribe the standard for the best class of apparatus only, but we must have a standard to satisfy all conditions. It is not always realized that the A. I. E. E. specification, while it gives the maximum permissible temperature, does not apply exclusively to the *best* construction, the *very best* class. You can get better than the rules provide, by specifying *lower* temperatures, but you should not go *higher* than 50 deg. rise. If you stipulate specially low temperature you must be prepared to pay a higher price, and sometimes, as in large, valuable machinery, it will be good policy to pay the higher price, but for the vast majority of small machines, the 50 deg. rise basis represents approved practise.

C. J. Fechheimer: It is always well, when considering alterations, to profit by the experience of others. The single rating, 50 deg. standard has been the practise in Europe for a number of years and European electrical machinery has been used in Mexico and South America. In Europe the single rating method has possibly worked out fairly well, because there the operators are generally men of intelligence and education. Many station operators in Europe are University graduates. In Mexico, on the other hand, where the operators are less intelligent, the number of burn-outs with European machines has been more frequent than with American machines built on the 40-deg. rise basis for normal load and with the usual 25 per cent overload. The 50 deg. single rating method puts the burden of proof for successful operation upon the operator.

The intelligence and education of the average operator in the United States is certainly less than that of the European, although of a higher grade than that of the Mexican. Furthermore, the indications are that the class of help in American power stations, mills, factories, etc.—especially the latter two, where generators and motors are used, will not improve. Therefore, if the single rating method is introduced, similar conditions will obtain in regard to burn-outs in this country to those which have existed in Mexico where European 50-deg. machines have been used. Even in the Commonwealth Edison Co., where a very intelligent staff is employed, machines have burnt out, as pointed out by Mr. Schuchardt. What then may we expect with the higher rated 50-deg. machines, especially if overloaded as the average station operator is liable to do?

I wish to call attention to a statement of Mr. Reist to the effect that with motors underloaded, as they are at present, the average

efficiency is reduced. I do not agree with this; in nearly all standard induction motors and commutating-pole direct-current machines, the point of maximum efficiency occurs at a load lower than normal with our present system of rating. Furthermore, the majority of purchasers endeavor to buy machines of such ratings as will enable them to just carry the load required. Hence, were the ratings of motors increased by the adoption of the proposed single rating, the customer would secure motors of materially lower, rather than higher, efficiency at the operating load. Although Mr. Reist's statement applies to the majority of alternating-current generators, the gain in efficiency by increasing the ratings of the alternators would usually result in an increase rather than in a decrease in the steam or water, etc., needed to operate the prime movers. Hence, from this point of view, the customer would lose rather than gain, if the ratings of all machines are increased.

Philip Torchio: The Committee recommends one rating for all apparatus. I state again that I have no objection to Mr. Merrill's rating of 90 deg. at hot spots for steam turbine generators and perhaps for waterwheel generators, but I think it would be a mistake to use the same standard for the class of apparatus referred to this morning, which is subject to overloads. For this latter class of apparatus I suggest 75 deg. maximum temperature. This would leave 15 deg. for possible overloading, though the amount of overload may not be specified. *I therefore recommend 90 deg. at hot spots for machines which are not subject to overload, and 75 deg. for machines subject to overload.*

B. G. Lamme: I think some confusion has come from the fact that the larger internal temperature gradients with high-voltage machines have been overlooked. Mr. Torchio wants a temperature of 75 deg. on his high-voltage machines. What he really wants is 75 deg. measurable temperature. What he is really after, although he possibly does not look on it that way, is to keep within the 100 deg. ultimate temperature, for the machines he has in mind have probably 20 deg. to 25 deg. internal drop, so that his 75 deg. measured temperature means probably 100 deg. at some point inside the machine. The sub-committee paper did not bring this point out clearly. We referred to 10 deg. to 15 deg. for low-voltage machines, but Mr. Torchio is using, to a great extent, high-voltage machines.

That also explains Mr. Stott's point. He referred to machines which ran at about 40 deg. by thermometer measurement, with air temperature not over 35 deg. cent., which would make 75 deg. measured temperature, and he thought 100 deg. ultimate was unsafe. I know the type of machine to which he refers, and I think that there is fully 25 deg. internal gradient from the hottest spot to the point where he could make his temperature measurement, so that I believe his machines were at least 100 deg. cent., and possibly hotter at times.

Mr. Schuchardt suggests 80 deg. as the limit, but in his machines, if I am not mistaken, exploring coils outside the insula-

tion were used in presumably what was considered the hottest part of the machine. His machines were also high-voltage, and presumably there was at least 20 deg. internal drop, so that his machines also are probably close to the 100-deg. limit at the hottest part. I consider that all these cases cited are pretty good proofs of the ultimate limits which we have set.

B. A. Behrend: I think we should limit the total temperature of the hottest spot and leave it to the ingenuity of the purchaser or his consulting engineer to find that hottest spot. If you do not do that, you open all doors to that lack of conservatism which the consulting engineer and purchaser would deprecate. It is enough to say that, if you build a thousand machines, those thousand motors or generators are not all alike. If you give us leeway on the hottest spots, we will make the majority of them, say 900 machines, to meet a total temperature of 90 deg. and the remaining machines might exceed that temperature by 10, 15, or 20 deg., or by almost any other amount. That seems to me to prove conclusively that Mr. Torchio is right in demanding that the total temperature guaranteed should be the temperature of the hottest spot in the machine. This will make the manufacturer conservative. He is forced to turn out the majority of his machines at a temperature which will be below the total temperature guaranteed, because he knows very well that the iron is not uniform, and the core losses thus vary greatly, and are subject to workmanship, and therefore temperature rises may occur which he did not expect, and he must guard against such contingencies by guaranteeing the total temperature of the hottest part of the machine. There is no escape from this conclusion. If the manufacturer tries to evade this point, he is trying "to put it over" the customer.

C. P. Steinmetz: The ideal method, naturally, would be to specify that the maximum temperature, at 40 deg. room temperature, should not exceed 100 deg. cent., that is, to specify the temperature of the hottest spot. That is very nice and I have no doubt the electrical manufacturing industry would be glad to do that, providing the consulting engineers and operating engineers will tell them how to find the hottest spot. It is up to the Institute to make some standard rules, some specifications, which shall be so framed as to be *commercially* applicable. At present the only practical method of measuring the temperature is by resistance or by the thermometer. Neither method discloses the temperature of the hottest spot. For many years people have imagined that these methods disclose the actual highest temperature, and that we have only 75 deg. or 80 deg. ultimate temperature in any part of the machine. Now, we know that these conventional methods did not disclose the highest temperature; that in cases where we believed the machine did not exceed 75 deg. at any part, there were interior parts which had temperatures of 100 deg. or more. The exploring coil shows temperatures a little nearer to the hot spot temperatures, but it does not show the temperature of the hottest spot anywhere in the insulation.

So you can see that the step in advance which we propose to take involves recognition of the hottest spot and limits the temperature of the hottest spot to not more than 100 deg. cent. But we cannot put that in any contract between manufacturer and customer because there are no means yet to determine the hottest spot, and so all specifications must still be based on the means now available for measuring temperature. This requires us to allow a lower conventional maximum temperature, say 90 deg. for Class A insulation. That is unavoidable. In short, we can *discuss* theoretical matters and the ideal conditions, but we *cannot meet* the ideal conditions in practise. That is the difficulty.

Now, what should be the limiting temperature for the hot spot? 100 deg. cent. has been advocated. Personally I believe that the hottest spot is safe at a higher temperature. Probably 100 to 105 deg. is quite safe, but we have no means yet of detecting the higher temperature, the hottest spot. And furthermore the whole question is complicated by the time factor. A temperature many degrees higher will occasion less deterioration *if only occurring during a few summer days*, than will a decidedly lower temperature *if continuously present*. We may say that if you take machines which are run hot, but do not burn out, which have been running for many years without trouble from heating, then the highest temperature which exists anywhere in one of those machines is the permissible hot spot temperature. But what is that highest temperature? Originally we imagined that that was what the thermometer and resistance methods of measurement showed. We have found, by getting more and more experience, that it is higher, and still climbing up, but I do not know whether we have, or have not, located the hot spots, and the fact is that the hottest spot is not a definite temperature which we can be sure of, but is the hottest spot in those machines which have been running for many years without burning out. I believe we are taking a step in advance to recognize this point, but we are not ready, and nobody is ready, to state what is the possible permissible maximum temperature for ordinary insulation which may be reached temporarily.

B. A. Behrend: If the hottest spot cannot be found, it is useless to say that its total temperature may be 100 deg. cent. If I cannot find it, I cannot guarantee its temperature.

C. P. Steinmetz: You may find it sometime—

B. A. Behrend: If I can find it sometime, then I like to know it and know its existence. I prefer to know that I am going to get a machine which will have parts hotter than those guaranteed.

C. P. Steinmetz: I mean, that you will know it some time in the future.

B. A. Behrend: It is surely better to know beforehand than to find out afterward. Since we designers of electrical machinery appreciate that there exist hot spots, unless we admit their

existence, we lead the people to think that our guaranty defines the hottest part of the machine. Let us admit the existence of concealed hot spots and guarantee a total temperature of 90 deg., and say that this refers to the hottest part of the machine. It will mean that ninety per cent of all the machines turned out by the manufacturer will have a readily measurable total temperature of 80 deg. The purchaser will get the advantage of this, and it seems to me he is entitled to this advantage. Standardization must be for the benefit of both the manufacturers and the user, and therefore let the manufacturer be a little more generous in his dealings with the customer.

There is one point which I cannot pass over, viz., the adjustment of the efficiency to the power factor for a given rating. In neither steam engines, gas engines, induction motors, nor alternating-current generators can we say that the maximum efficiency, the best regulation, or the highest power factor, are at the point indicated by its rating. The maximum rating of machinery places the burden on the user and his consulting engineer, and it seems to me that twenty years of education should have given the customer, if not the consulting engineer, an opportunity to learn how to make allowance for the conditions he has to meet. If a 50-h.p. motor is a 50-h.p. motor maximum rating, and if I am a little doubtful as to whether my plant requires 50 h.p. or 55 h.p., I shall take a larger motor. If I wish to use ordinary cable, or a piece of shafting, or a bearing, and consult a manufacturer's catalogue, I must apply the same reasoning. There can be therefore no objection to a single rating on this score. Why the electrical engineer alone should be less able to use his judgment than the mechanical or the civil engineer it is hard to see. When we design a bridge we must know the elastic limit of the materials used in it. The really important issue lies in the application of the designer's judgment to the safety factor to be employed.

I wish to say a word regarding the use of the emblem of the Institute on the name-plates. It creates the impression that the stamp of approval of the Institute has been placed on the manufacturer's apparatus, which we know is not so. It is not compatible with the dignity of the Institute. The single rating is a sound movement, and the only point to be decided is how to use it, or whether to deceive ourselves into believing that we have cooler machines than we actually have. I do not approve of any species of make-believe. If I am to be robbed I want to know it; and if I am to be deceived, I want to know it also. If I have to use machines which will show a temperature rise of 115 deg. total rather than 90 deg., I want to know it. It is perfectly feasible to embody it in the same scheme now contemplated by the sub-committee.

R. F. Schuchardt: One more reference to finding the hot spots, with regard to having the customer find them, as suggested. It may be interesting to state more of the details of the experience

mentioned in my previous discussion. At the time of the breakdown of this particular unit to which I referred, the temperatures were being taken according to the specifications in the contract, and the temperature limits of the contract had not been reached at the time of the breakdown. The customer then set about to find the hot spot, and with the permission of the manufacturer, put these exploring coils at the place where the designing engineers of the manufacturer said would likely be found the hottest spots. Then we made tests to find what is the safe maximum temperature at which to operate that insulation, and we found this to be 80 deg.

Charles P. Steinmetz: If the designer or the manufacturer, or anybody else, only knew where the hottest spots are, and how to find them and measure them, the specification of the maximum temperature at the hottest spots would be the most satisfactory to the manufacturer, operating engineer, consulting engineer and everybody else. Unfortunately, that is not the case. We may *believe* that a certain region will be hotter, and even that it is the hottest place, but we do not *know* that with certainty. We know that the place which Mr. Schuchardt referred to just now was the hottest place which could be reached. Quite possibly somewhere else, at a place not reached by the exploring coil, there may be hotter spots, and that is the difficulty.

I sympathize with Mr. Behrend that he does not want to have something sold to him which is not as described, but if he will kindly follow the suggestion which we put forward at the beginning of the convention, not to make destructive criticism but constructive criticism, and tell us how to go to work and locate the hot spots and how to measure them, he will be a great factor for good in the advancement of the electrical industry. But as long as we do not know how to find the hot spots with any certainty, or how to measure their temperature, we have to do the next best thing, and measure the temperature in ways practically available. I believe it is a step in advance to recognize the existence of the hot spots, to recognize that the measured temperature is not actually the maximum temperature, but that there is somewhere a higher temperature, and furthermore, to recognize that the highest temperatures exceed the measured temperature by various amounts, (depending on the condition of the machine, on the design, on the insulation), which exceed the measured temperature by 5 deg. or 10 deg. in some machines, like direct-current machines, or exceed the measured temperature by 20 deg. (or possibly even 30 deg.) in other machines, like those with high temperature, high voltage, heavily insulated, heavy armature coils. But we have reached something in recognizing that we want the assistance of all engineers to help us find where the highest temperatures are located and how to measure the highest temperatures. We will be glad to standardize the specification of the highest temperature and the methods to find it, if you can give us some feasible method of doing so.

W. L. Merrill: There is quite a lot of discussion on this ultimate and high temperature, and it must be remembered that it is only due to those cases in which the room temperatures are 40 deg., which is considered as the high limit of room temperature recognized by the Institute. Anything below that would be a factor of safety, which you would have in addition to these maximum temperatures. In taking up this paper, it was my understanding that the 90 deg. was to be the maximum ultimate temperature, as determined by methods approved by the Institute, either at present or in the future, whatever those rules should be. I think, perhaps, that would reconcile some of this discussion, and I would like to put in a hypothetical question—if there is a method determined, or if our present method, plus a correction which has been mentioned in the papers, were put into practise, what is the consensus of opinion of the various gentlemen who have just discussed these papers, or are interested in the subject, if the limit were put at 90 deg., if that would meet their approval, or rather, should it be 100 deg? In other words, is it 100 deg. that must be the maximum for fibrous insulation or 90 deg.?

There is one point I want to touch on—the question of bearings. The sub-committee thought it would be attacked a great deal more on the matter of bearings, perhaps, than some other things contained in its report. The question of limiting the temperature in the bearings of electrical machinery, to my mind, is not very good practise. Is there any gentleman here who has purchased a steam engine and questioned the veracity of the manufacturer as to what the heating was to be in the steam engine bearing? Is not the same true with waterwheels? Is not the same true with line shafting, gas engines, or any other piece of machinery that is purchased, that the question of bearing temperatures is not raised? I have a particular case in mind, which I think shows the fallacy of limiting the design of electrical machinery, we will say handicapping the design, by limiting the temperature of the bearings. In the case referred to, vertical waterwheel-driven units were used. At the time the engineering was done the waterwheel manufacturer was to supply the thrust bearings. They were put below the generators, and there was no reason to suppose the bearings were not all right to carry the load and give a good account of themselves. By reason of later development, the man who was to install these units decided to have the bearings on top of the generators, so they now became part of the electrical equipment, and they had to be designed to meet the temperature rise of the Institute. It seems to me electrical machinery should be put in the class of other machinery when it comes to the question of bearings.

One more point in connection with the bearings—we will assume that we have a machine in which the engineer has decided on a 5-in. shaft with a 3 by 1 bearing, making a 15-in. bearing housing. The rubbing surface of that bearing is long.

and it might heat beyond the temperature limit set down by the A.I.E.E. at the present time. That temperature can be materially lowered by shortening up the bearing housing. We could cut it down to a 5 by 10 bearing, and it is possible to still lower the temperature of the bearing, and the bearing is not as good for working as at that higher temperature limit. Another point was the rating of the temperature limits of the bearings at 50 deg. That is a physical impossibility, although we are supposed to do it today. Take the case of a small totally enclosed motor, a mill motor or railway motor, where the temperature is practically uniform throughout the whole machine, the bearing must necessarily be approximately the temperature of the rest of the machine. On the rest of the machine we are allowed 75 deg. or 90 deg. rise, for non-fibrous insulation, and necessarily the bearing must go up to that, there is no help for it. I suggest, Mr. Chairman, that you get an expression of opinion from Mr. Torchio, and various other gentlemen who have discussed this paper, if their understanding is tha tthe guarantee of the maximum hot spot should be 90 deg. instead of 100 deg., whether that would meet their objection.

Philip Torchio: In summing up the discussion, Mr. Chairman, I do not think you have taken cognizance of the point of view I have been trying to present. There is a serious objection to using the same limiting temperature of 85 or 90 deg. (which is required and allowable for turbo-generators) for that class of apparatus which is subject to overloads beyond the control of the operator or user. I want to emphasize the point that you cannot unify two distinct sets of conditions. You cannot have the same rating, the same maximum temperature, for the turbo-generator and for the synchronous converter or the motor.

Charles P. Steinmetz: I wish to say that when considering the question whether 90 deg. or 100 deg. should be the temperature of the hot spots, we should give consideration to the present existing apparatus, to all those many small motors which are turned out by the thousands by many manufacturers, in most of which apparatus, with a room temperature of 40 deg. cent., the hottest spot is above 90 deg. cent. All of this apparatus would have to be redesigned, which would be a very serious matter, not to the big manufacturers, who could easily afford to do it, but to the small manufacturers, who would have to redesign their motors and other machines to make them larger.

I would like to know whether the smaller manufacturers would be willing to rate down their apparatus, or to make them larger, and bring the limits of temperature to 90 deg., or less, maximum temperature, where it is now higher. It may not be higher by the conventional method of measuring, but undoubtedly most are higher, today, at 90 deg. maximum temperature, on the basis of 40 deg. room temperature.

W. H. Powell: The motor-generator set referred to by Mr. Torchio would be classified as A 3—Continued Pulsating

Service, or under certain conditions as class B 3—Short Time Pulsating Service. Other limitations prevail besides the ultimate temperature. The recommendation of the committee, viz., that apparatus be rated on the basis of ultimate temperature, and that no overloads be specified except momentary overloads, applies only to apparatus falling within class A 1—Constant Service, where load is continuously applied.

Charles F. Scott: The fluctuating viewpoints in this discussion raise the question, what do our Standardization Rules stand for? What is their purpose? What is standardization? Some things cannot be standardized in simple terms. For example, a few years ago the Standards Committee took up the rating of railway motors, which were given a "one-hour rating" in our old rules. A sub-committee undertook a revision; meetings were held at which engineers from manufacturing and operating companies and consulting engineers to the number of some fifteen or twenty were present, some of them among the most prominent men in the Institute. The matter was discussed first one way and then another, and we kept getting further and further from a conclusion. We adjourned for a week. Then Mr. Armstrong came with diagrams and curves to show that the one hour rating was inadequate and that a certain method was better. Mr. Storer came with his data to show that something else was best. Everybody seemed to be conscience-stricken because we could not come to a conclusion, and tell how to rate railway motors in a simple sentence or paragraph, and the chairman suggested that we had better give it up, as agreement seemed impossible. A member suggested—"Maybe it is impossible, maybe the fact that the performance of a railway motor, which has to do so many kinds of service, cannot be expressed in terms which are simple, is the lesson we have learned in our discussion here." Each of those meetings started at four in the afternoon and ran to seven or eight in the evening, and the outcome was not to express the rating of a railway motor in two or three lines but to set forth methods of selecting a motor for given service in a couple of pages in an appendix to our present rules.

What are we now attempting to do with respect to the rating of motors? Are we not attempting to express in a few paragraphs the characteristics of all motors? The types of motors and the conditions of service are so diverse that it is impossible to make simple classifications which will be adequate and complete. Stationary motors must meet a range of service conditions more extensive and more erratic than railway motors. The latter are fairly definite in type and in the nature of the service to be performed, and yet they do not admit of any simple method of rating; hence any elementary or simple classification of stationary motors must be rather general in its nature. In the proposed classification, there does not seem to be any discrimination between series motors and shunt motors, and the divisions of service conditions into several classes is only a first approximation,

as can readily be seen if one selects several specific cases and endeavors to adapt them accurately to the proposed classification. If classifications were to include accurately all conditions, there would have to be a hundred or more divisions, instead of half a dozen.

What then do the Standardization Rules attempt to do? I have been a member of the committee for several years, and, speaking generally, our object has been to express what is good practise in definitions of terms and in methods of measurement. When, however, the Standardization Rules are used by the operating or designing or testing engineer, they are often regarded as something which should be absolute and complete, and the rules are criticised if they do not seem to meet definitely each particular case which may arise. The past policy seems to me to be indicated by this sentence in connection with transformer insulation tests: "The voltages and other conditions of test which are recommended have been determined as *reasonable and proper for the great majority of cases* and are proposed for general adoption, except when specific reasons make a modification desirable." In other words we are not making a set of specific rules, but we are giving sanction to practises which are good. It is expected that intelligent common sense will be used in applying the Standardization Rules. We see, for example, that it is good practise not to have the temperature of a motor rise above a certain limit, but Mr. Merrill has just pointed out the absurdity in carrying this rule too far and making a bearing of one temperature if it is considered to be a part of a dynamo and another temperature if it happens to be considered as a part of the waterwheel.

We are discussing rating; what is rating? It is the assigning of certain values to express the capability of a machine. These values depend upon the quality of its materials, upon its regulation, insulation, temperature, and other factors. All these are indefinite; they may be expressed in curves. There are no definite absolute limits like the length of a yard-stick or the weight of a cubic inch of copper. The selection of the limits which fix the rating is a matter of judgment. Take, for example, a completed motor which has lost its name-plate, and attempt to fix its rating and to determine the volts and amperes and speed and horse power that should be put upon the name-plate. Tests may be made, but judgment must be applied in selecting definite limits.

When a motor is sold, its name-plate joins together two things —its past history in the factory, which determines its electrical capability, and the service it can render, which is its mechanical performance. The motor drives a shaft and the shaft drives the load. Torque and speed are the two things which the motor produces, and torque and speed are the things which the load requires. The requirements of the load are subject to definite variations in the relations of torque and speed and time. Our

problem is to specify the capability of the motor in torque and speed and time in such a way that its adaptation to power service requirements can be determined. If we were to make classifications which covered all service requirements in point of variable load and time conditions, we would have a hundred classes, instead of the half-dozen which have been proposed. Obviously, therefore, the motor classifications proposed are not complete and exhaustive, but they simply indicate what a motor can do under a few typical conditions. This must be supplemented by an intelligent comparison between the actual service requirements and the specified classifications.

What the motor specifications are accomplishing is to define, more definitely than has been done in the past, what a motor will do under several sets of conditions. The commercial engineer must then, with this larger knowledge of motors, make his selection of the proper motor for his specific case. We are assisting the seller and the buyer, not by covering definitely the various conditions of service, but by defining more completely the capability of the motor. We define what the motor can do under specified conditions, but we cannot define what it will be required to do in operating a lathe or a hoist or a pump.

The proposed specifications are general; they do not even distinguish between series and shunt motors. We simply lay a good general basis, and our rules cannot be extended much further, unless different types of motors are treated as we have already treated the railway motor, by giving to each type an extended dissertation as to how the selection is to be made for each type of service.

Comfort A. Adams: There are two functions of rating; first, to enable the customer to compare the prices of different manufacturers; and second, to enable the customer, or his agent, the engineer, properly to choose a machine for a given duty or service. It is obviously impossible for any set of rating rules to cover all kinds of service. Those who have had to do with the choice of motors for a special purpose realize that there are hardly two cases which would be covered exactly by any simple system of rating. The important thing, then, is that we come to some agreement. It is not so important that the chosen temperature rise be absolutely safe at all times, as it is that we understand what that temperature rise means. Just in so far as we know by experience or by computation, or both, what the difference is between the temperature of the hot spots and that measured by any particular method that we may agree upon, can we make intelligent use of the corresponding system of rating.

I do not agree that we must adapt our method of rating to the unintelligent unadvised customer who buys a machine on the basis of its h.p. rating, while guessing at the duty. That class of customer is a rapidly diminishing one, and should not be made the excuse for saying one thing and meaning another.

Charles F. Scott: What is the relation of the Institute to buyer and seller? We are a professional body and not a commercial body. It is our function to express what is good professionally. This was summed up in excellent form on the night of the original discussion which led to the formation of the Standards Committee, fifteen years and one month ago tonight, when Dr. Steinmetz said, that standardization came under two heads: first, a definition of terms, and second, a definition of methods of tests. We will do well to adhere to this scheme, doing professional work which directly concerns us and let the application to commercial work go to others.

Alexander M. Gray: In my previous remarks I attacked the clause on bearings, and I am still unconvinced on that point. Shaft bearings are in a different class from motor bearings; they squeak long before they break down, whereas a motor bearing gives no warning; and I still contend that the temperature of the oil in the bearings should be limited to 70 deg. cent. If the bearings are to be hotter, let us know about it, and put it in the specification.

I consider that Mr. Behrend is right in the attitude he takes about the use of the Institute initials on name-plates, but we should have something on the name-plate to show that the machines were given a single rating and not one with an overload capacity.

B. G. Lamme: I have been listening to many statements which are apparently in disagreement, and I will therefore try to do some averaging. It seems to me that many of the apparent discrepancies which have come up, are due to looking at the problem from a wrong basis. We all think of the temperatures of machines based on our everyday experience, but our everyday experience is really at 20 deg. or 25 deg. air temperature. On that basis we think of a machine which reaches 75 deg. cent. by measurement as a very safe machine. If, *at the same air temperature*, that machine is loaded until it reaches 90 deg. cent., we consider it is beyond the safety limits. That is correct, because, on the basis of 20 deg. or 25 deg. cooling air temperature, the machine showing 90 deg. temperature by measurement is an unsafe one in service, for such machine will probably be at least 100 deg. cent. at the hottest part, and therefore any increase in the cooling air temperature puts the machine above the danger point. However, if the 90 deg. measured temperature is always tied up with the 40 deg. cooling air temperature, then the case is quite different, for at ordinary air temperatures, the machine then has only 80 deg. to 85 deg. ultimate temperature. In other words, when we think of 100 deg. as the ultimate limit with this proposed method of rating, we must always think of the 40 deg. air temperature in connection with it.

I also wish to emphasize one point, namely, that if the ultimate temperature limit is set at 90 deg. cent., instead of 100 deg. cent., that is, if 90 deg. is to be the hottest spot inside the machine,

then on the basis of cooling air at 40 deg. cent., a vast majority of the apparatus now built in this country will not come inside the new rules, and this applies in particular to many lines of apparatus which are now thoroughly successful and have given satisfactory service in every way; that is, if we adopt a 90 deg. standard as proposed, then we cannot live up to it rigidly without derating a great deal of thoroughly satisfactory apparatus. This appears to me as one of the strongest arguments against the 90 deg. ultimate limit. If a rule or limit is set so that it will condemn thoroughly satisfactory apparatus, then the limit must be wrong.

C. L. de Muralt: Prof. Scott pointed out a moment ago that we are essentially a professional body. That is true, but we are a unique professional body. Many of our members are representatives of the manufacturers. Some may consider this as a difficulty. I do not look at it that way. I think that we can be greatly benefited by the presence of the manufacturers and by the work which they are doing to help us establish these standardization rules. Imagine a strictly professional body establishing standardization rules. It would be much more difficult.

We have really had three different views presented to us at this convention. We have heard the manufacturer say along what standard lines he is prepared to build his machinery and guarantee it. We have heard the operator state what he thought the manufacturer should do to help him buy machinery for special conditions. And we have heard the consulting engineer present his particular troubles in bringing the two together.

As a matter of fact, listening in the background, it seemed to me that all were pretty thoroughly agreed and I think we pretty nearly accept what Dr. Steinmetz and Mr. Lamme suggest to us. Two things must be considered in order to satisfy ourselves on machine rating. One is the maximum overload capacity. The other is how much of a load, continuous or intermittent, will the insulation stand? The maximum overload capacity, as I understand it, has not been touched upon at all in this report, nor has it been much mentioned today. In most cases it is a well defined point. We may, therefore, as well limit ourselves to the question of protecting the insulation. That means determining the temperature beyond which the insulation will be damaged, and that is what I understand the sub-committee reported on. Most of the men who talked on this subject agreed that we want that temperature laid down definitely. Whether it be 90 deg. or 80 deg., or 100 deg., is possibly subject to further discussion, but I think most of us are satisfied that 90 deg. would be all right and we want the hottest point of any machine to be not in excess of 90 deg. if it is in touch with the insulation.

Then the only question remaining is the one brought up by the second paper, namely, how shall we make our ratings so that the above point is actually taken care of. Many of us have come to the conclusion that it is not well to have different ratings. It

is safer to have the manufacturer rate his machines for running continuously, that is, for the worst possible operating condition from the point of reaching maximum temperature. Then, if a certain machine is to be run under different conditions, not continuously, then it is up to the man who buys that machine, or to his adviser, to find out how his particular run differs from the continuous run. This may reasonably be made the subject for another report by the Standards Committee, or possibly it may necessitate research investigation by an independent man presenting a paper, showing how certain specific runs or typical runs do make the temperature vary. Thus far it is not at all definitely laid down by anybody, and simply to anticipate a certain number of typical runs, that may or may not be met in actual practise, seems to me, and has apparently seemed to most of those who spoke on the matter, beside the point.

I maintain therefore that the outcome of this discussion is that the Standardization Rules should be on the basis of no point of any machines reaching a higher temperature than 90 deg. after a continuous run of sufficient duration to bring about maximum temperature.

H. M. Hobart: There have been intimations that the manufacturer had some object in this matter other than providing for the best interests of the industry. These intimations were not put forth strongly, but they have been repeated in several quarters. I have played different parts in the electrical industry, and I am now associated with a certain manufacturer, and I am satisfied there is absolutely no doubt about it, that the manufacturer has no greater concern than to get at the best results for the electrical industry. There is nothing altruistic in this standpoint; it resolves itself into a matter of enlightened concern for the interests of the shareholders. The manufacturer recognizes that it is a good investment to spend vast sums of money making investigations, and he thus secures special information which he gives freely to anybody who will take the trouble to read it—as I say he spends vast sums to get at these facts, and it has led his engineers to have certain views that such and such things are best. They have arrived at these views as the result of elaborate tests. If it can be shown that they are wrong, the manufacturer is willing to at once change his plans. What the manufacturer wants is to promote the very best interests of the electrical industry as a whole, and he particularly wants definiteness in the matter of standards, some definite set of standards. That would be arrived at by this single rating system. If anyone has a necessity for using lower or higher temperatures, it is simply a matter of slide rule transference, for him to decide which size of machine he requires. The matter is far simpler than one would gather from the long, though very interesting, discussion which we have had about it.

B. A. Behrend: I feel constrained to say a word in regard to the remarks of Mr. de Muralt and Mr. Hobart. The relation of

the manufacturer to this Institute is a question I do not intend to discuss. I do, however, wish to point out one thing, viz., that the manufacturer is responsible for the old code and for the last edition of our Standardization Rules, and that the application of these rules to actual conditions favors the manufacturer. For instance, the application of the rules to the determination of the regulation at 100 per cent power factor would give 4 per cent regulation, while in reality the regulation of the generator may be 8 per cent. I shall be satisfied with this single reference—which I made eleven years ago before this Institute while advocating the same system of determining regulation which you have now come to recommend. I do not charge, as Mr. Hobart's remarks would imply, and I do not wish to be understood as saying that the manufacturer has done this with an evil intent, as in the end he is responsible for results, and if he sends out poor machinery he must, and does, make it good.

Comfort A. Adams: It is absolutely impossible to devise a system of rating which will take account of all kinds of overloads. The safe limit of measurable temperature differs for different overloads, since the difference of temperature between the hot spot and the point at which the measurement is made is greater, in a given machine and with a given hot spot temperature, during the transient period of a short heavy overload than under steady conditions, owing to the heat capacity of the insulation. This is appreciable only in machines of comparatively high voltage and thick insulation.

A. E. Kennelly: It seems to be the consensus of opinion that a single rating for electrical machines is desirable, based on the maximum measured temperature attained. Differences of opinion enter as to just what that maximum measured temperature should be. It is generally admitted, however, that the maximum internal temperature of class A insulation should be 100 deg. cent. That internal wall temperature is ordinarily inaccessible, and we must at present be content with measurements of the maximum temperature of the outside wall. The committee recommends 90 deg. cent., thus allowing 10 deg. cent. for drop of temperature in the wall. But whatever maximum measured temperature of the outside insulating wall is adopted between the limits, say of 80 deg. and 95 deg. cent., some allowance will have to be made by electrical engineers in ordering large machines, for the special conditions under which those machines are to operate. A considerable number of machines may be ordered for continuous service at their nominal continuous rating under the new rule; but many machines will call for the exercise of reasonable judgment. If, for instance, a generator is to be ordered for a mill, in a cold climate, with the expectation that it shall have to deliver 1100 kw. and no more, for 10 hours a day, then a machine of perhaps 1000 kw. continuous rating might be sufficient; whereas if the generator were to be used in the tropics, with the expectation of delivering 1100 kw. ordinarily, but with

occasional demands for 1500 kw., then a 1500-kw. machine might have to be ordered. Since, therefore, engineering judgment in the selection of a machine cannot be avoided on any basis of continuous rating, the exact value of the maximum measurable temperature is of secondary importance. The matter of primary importance is some one clearly defined maximum measured temperature to suit the average requirement, and then data from which the maximum internal temperature of the insulation can be predicted for large or special machines, from a given assigned schedule of load through the 24 hours.

A. M. Rossman: May I offer a suggestion which, I believe, is in conformity with the recommendations of the sub-committee on ratings, yet would meet the objections raised by several of the operating engineers? The suggestion is, that the recommendations of the sub-committee be adopted but that at the same time, a system of factors be established which would guide the purchaser in the selection of the proper size of machine for the class of service it is to perform.

For instance, in buying a new railway synchronous converter he would buy a machine 1.5 times the rating of his present machines, provided his present machines were purchased on the basis of 50 per cent overload for two hours. In buying distributing transformers he would buy for the same duty transformers 1.25 times the rating of his present transformers. We are already used to turbo-generators rated for maximum continuous duty and these would therefore have a factor of 1.

I thoroughly believe in the system of single rating because (1) the manufacturer builds a machine to meet one definite temperature condition, (2) the consulting engineer bases his acceptance of the machine on a single temperature test, and (3) the purchaser has a common basis of comparison between machines of different manufacture.

C. E. Allen (by letter): The paper by Dr. Steinmetz and Mr. Lamme is of greater interest at this time than most of us realize, but it is the writer's opinion that there are a number of interesting phases of the subject which they have not touched upon. They state that the durability of insulation must be considered from two standpoints, *i.e.*—mechanical and electrical. I believe they should have stated three—the third being the "method of preparing and applying."

As their paper is written more with a view to guiding the future than criticising the past, it seems just that they should have considered the improved insulation and methods of application in reaching a conclusion for the basis of a recommendation.

In order to understand more thoroughly the present and future methods, it is necessary to dwell somewhat on the past. Until very recently the methods of applying insulations in most of the classes of apparatus have necessitated the insulation being made in more or less of a flexible form, which has resulted in a larger amount of insulation being used than was actually neces-

sary or desirable. By necessary I mean that the uniformity of the insulation could not be depended upon and that, in order to be sure of a predetermined value, a greater amount was used, with the result that an occasional piece of apparatus out of the different classes could be selected which would show a much higher test voltage than it was actually designed for; yet as a complete line the average would probably not exceed the designed value. This increased amount of insulation also had its influence on the heating of the apparatus and resulted in a less uniform temperature and a greater maximum temperature of some one part of the apparatus. It was possible for this excess temperature to vary considerably in different pieces of apparatus of the same design and it was very possible for this temperature to be excessive and result in the short life of the insulation and resultant failure of the apparatus.

This past practise also permitted a defect to be taken advantage of, in that where occasional pieces of apparatus would stand a higher test voltage than designed for, many times the electrical fraternity were led to believe that the insulation value of a certain line of apparatus, based on a test of one individual piece, was much greater than the actual average of the line, while the question of the excessive temperature as a result of this, which would have a decided influence in determining the life of the apparatus, was not fully taken into consideration.

The more modern methods of preparing and applying insulation, particularly where mica is used, have resulted in the insulation being formed into a proper shape and assembled with the apparatus in such a way as to eliminate any distortion of the same, which would otherwise be likely to result in a marked decrease in its insulating value. With these new methods, which also involve certain new elements in holding the mica together, it will not be necessary or desirable to use the excessive amount of material that has been used in the past.

While it may not be probable that one piece of apparatus out of a line can be selected that will stand as high a voltage as in the past, yet the average of the line can be depended upon, with a corresponding reduction in the maximum temperature. This will not necessarily mean, however, a lower average temperature, but a more uniform temperature, resulting in apparatus that will have a longer life.

The new form of insulation and method of application is also more durable from a mechanical standpoint and is not as readily injured by the contraction and expansion of the copper and iron in the apparatus where it is used.

While there is no question of a doubt that the later methods are a decided improvement and an advance over the older methods, yet it is going to be possible from comparative test, as formerly pointed out, to deceive a prospective purchaser and demonstrate to him, on the basis of one piece of apparatus, that the standard is not as high as it has been in the past. It is,

therefore, very desirable that that part of the electrical fraternity representing the central stations, as well as that part representing the manufacturers, cooperate with the Institute committee and follow out its adopted standards.

When considering that this organization represents the foremost talent in the world, its recommendations should be taken verbatim and every central station and manufacturer should insist upon meeting only the A. I. E. E. standard, and not permit a higher value in one characteristic at the sacrifice of another. If this is followed out the result is going to be more satisfactory to the electrical fraternity as a whole.

E. A. Wagner (by letter): If we were able to build up electrical apparatus with homogeneous insulating material throughout, there would be no difficulty about classifying different electrical apparatus as outlined in the paper on "Temperature and Electrical Insulation." It seems to me that it would be decidedly difficult for anyone to determine whether some classes of apparatus would be class A, B or C. This is particularly true of the proposed class A and class B apparatus. Take the case of generators in which the slot insulation is made up of mica or asbestos, or equivalent refractory materials. In these slots there are windings made up of the cotton covering which come under the class A. An injury to the insulation between turns would put such a piece of apparatus out of business, yet would not necessarily communicate a ground to the core. The same thing holds true of certain makes of transformers. It might be argued that if there is any cotton present at all, then the apparatus belongs to class A. If this is the case, then it would seem that the classification should be limited to two, one class which can burn out, another class which cannot, the latter class representing rheostats, heating elements, etc.

In the case of stationary transformers, the paper on rating loses sight of one important class of transformers which I think should be considered in the Standardization Rules. I refer to auto-transformers, sometimes called compensators. It has been the practise in some cases to rate these devices by the amount of the work transformed, considering this as the output. However, in any device we must consider the output in kilovolt-amperes as the product of volts and amperes delivered at the terminals, without regard to the work of transformation taking place inside of the case. It will, therefore, be seen that we have two methods of rating such a device, and the practise has recently been adopted of rating these devices both in kilovolt-amperes transformed and kilovolt-amperes output. I believe this method of rating provides for the classification of the apparatus, both from the standpoint of apparent work done and actual work done. One rating without the other can very readily be very misleading, and I think the Standards Committee should include a classification of this kind in the revision of the rules.

G. I. Stadeker (by letter): Although it is evident that a new system of ratings is highly desirable at the present time, it is advisable to make these changes slowly instead of confusing the vast number of buyers of power apparatus, who have but a slight technical training, by making several radical changes all at the same time.

The first step would be to change the method of rating as suggested in the paper under discussion by establishing the output on an ultimate temperature, instead of on a temperature rise, basis. But the suggested change in rating of motors, from the horse power to the kilowatt basis, would create considerable confusion. For instance, assume a motor-generator set, rated at 10 kw. This would ordinarily mean that the generator is 10 kw. There could be no misunderstanding in the present method of rating. But under the proposed system, a motor-generator set could be rated at 10 kw. when the motor driving the set was rated at 10 kw., with the result that the generator itself could not have a capacity exceeding 8½ kw. or 9 kw. This is one possible source of confusion.

Another source of misunderstanding, if motors are rated in kilowatts instead of horse power, is that the general public would probably assume that a one-kw. direct-current motor could be used as a generator to develop one kw. This would not be true. For instance, the ampere capacity of a 10-kw., 230-volt generator is 43.5 amperes. If this machine operated as a motor on a standard 230-volt circuit it would have a capacity of only 43.5 amperes at 230 volts, whereas a 10-kw. 230-volt motor should have a capacity of 50 amperes (assuming an efficiency of 87 per cent). The 10-kw. generator could, therefore, be only rated at 8.7 kw. as a motor. Although the reasons for this are perfectly clear to the engineer, it would be confusing to the non-technical public, inasmuch as both generator and motor are given the same rating. This condition represents an apparent inconsistency in the new method.

Until the new system of temperature ratings has thoroughly adjusted itself, we should continue to use the horse power as the unit of power.

J. W. Welsh (communicated after adjournment): From the standpoint of the operating engineer, any method of rating apparatus in which the full load continuous output can be secured only at the expense of attaining the maximum permissible temperature rise, hardly appears to be a safe basis of operation.

In eliminating all overload ratings for continuously rated apparatus it is believed that too radical a step is being taken. There are certain usages where this is less objectionable than others. For example, in a large generating station where the load is comparatively steady it is possible to operate a machine continuously at its maximum rating. At the other end of the system and at intermediate points where the diversity factor is lower, the fluctuating nature of the load as well as the prominence

of the peaks make an overload capacity in the apparatus highly desirable.

The maximum capacity required is determined by the peak. It is believed that for the same materials and ultimate temperature in a given piece of apparatus, a greater ultimate rating on the basis of a short peak can be given, than would be permitted for the maximum rating on a continuous full load basis. In other words, a maximum-rated machine, if operated at less than rating, should pull an overload above its maximum continuous rating for a short time with the same ultimate temperature. Moreover, as brought out in the paper of Dr. Steinmetz and Mr. Lamme, if the same ultimate temperature is attained both with peaks of short duration and for continuous operation, the life of the apparatus is increased in the former case.

A further objection to rating up apparatus to its maximum continuous output, is the bad effect on certain operating characteristics, such as the starting and running torque of motors, the commutating limit in d-c. apparatus, etc. The values proposed for these are considerably less than those which were guaranteed in specifications under the present rules. From this it appears that the margin of capacity has been cut down here as in the case of temperature rise. In other words, it is difficult to secure good operating characteristics at what amounts to overload on the old basis.

The recommendation is therefore made, that the full load continuous rating be fixed on such a basis as will still permit of overload ratings for a one-hour or two-hour peak in addition to the momentary overload. The ultimate permissible temperature should then be adjusted to meet these ratings.

Referring now to the report on *Method of Rating Electrical Apparatus*, in specifying the ultimate temperature as the basis of rating apparatus rather than the temperature rise, it is believed the exactness of the specified rating is sacrificed. If the ultimate temperature is fixed, it is also necessary to fix the temperature of the cooling medium. If, for example, the ultimate temperature is fixed at 90 deg. cent. and the cooling air at 25 deg. cent. the temperature rise is 65 deg. cent., which will certainly permit of a greater rating than if the cooling air is taken at 40 deg. cent., which corresponds to a 50-deg. rise.

While it is possible to measure the ultimate temperature of apparatus with a considerable exactness, it is believed that the determination of the true temperature of the cooling medium will be found more difficult.

The temperature of the cooling medium should be taken as that of the outside air when this is brought in through ducts for cooling purposes. To take the room temperature immediately surrounding the machine appears to be charging off the temperature rise twice, since the room temperature is the result of the fact that the heat given off from the apparatus has raised the temperature of the cooling medium. The room temperature

in this case has no more bearing on the situation than has the hot temperature of the cooling water leaving a water-cooled transformer.

In case of apparatus operated without forced ventilation it is obviously unfair to take the air temperature in the immediate vicinity of the apparatus, since, as in the above case, this represents a rise in temperature of the cooling medium due to the heat generated in the apparatus itself. If there is no other heat-emitting object in the room in which the apparatus is located, and the natural ventilation through the doors and windows is such that with the apparatus running at rated load, a constant temperature gradient is reached within the room, then the case becomes similar to that of forced ventilation, the only difference being the rate at which cold air is supplied from the outside. The temperature within the room will of course vary at different points, being hottest near the apparatus and coolest at the doors or windows. In this case also, it is believed that the temperature of the cooling medium should be that of the incoming air as measured within the room, near the doors and windows.

Edmund C. Stone (communicated after adjournment): Operating men cannot take too much to heart the fact, so clearly brought out in the paper, that each overload producing an excessive temperature materially weakens the insulation of the machine and shortens its life by a perfectly definite amount.

While the gradient of 10 to 15 deg. of the hottest parts above the rise obtained by conventional methods is sufficient for machines of the best design, many manufacturers are offering apparatus having the same temperature guarantees but much less ventilation. A purchaser, therefore, is not always protected by a measurement of rise by the usual methods—he must either actually measure the temperature of the hottest parts of the machine or be able to judge fairly accurately the value of the ventilation actually provided.

Machines in the past have been so liberally designed that they have actually been good for a continuous load much above their rating. It is now possible to predetermine the performance of a given design far more closely than in the past. Hence machines now put out come very close to the guaranteed rise. If, under these conditions, the full-load guaranteed rise is made the maximum safe rise of the machine, it is obvious that the customer will not get as much for his money as heretofore.

Regarding the question of a single rating, it seems to me that in addition to the rating the manufacturer should furnish a "time-overload" curve, showing the length of time that a machine can carry various overloads.

This is of supreme importance because of the sharp peaks that are a characteristic of many types of commercial load. For instance, one substation has a one-hour peak 35 per cent in excess of its normal load, during three months of the year only. It would be needlessly extravagant to buy for this station apparatus having a continuous rating equal to this peak.

For such reasons as this it is impossible for any operating man to use his apparatus economically unless he has a good knowledge of its heating characteristics.

William F. Dawson (communicated after adjournment): Considerable timidity has been expressed over the recommendation of Dr. Steinmetz and Mr. Lamme to establish a maximum measurable temperature of insulation made from organic materials, as 90 deg. cent. The testimony of Messrs. Steinmetz and Lamme, frequently repeated, that they have found this a conservative limit should, in view of their great experience, satisfy most critics.

Their recommendation is to a large extent supported by most exhaustive and interesting tests made at the National Physical Laboratory, Teddington, London, for the Engineering Standards Committee (British), in a paper entitled "Report on Temperature Experiments" and read by Mr. Raynor and Dr. Glazebrook before the Institution of Electrical Engineers, March, 1905.

Attention is also directed to a paper on "Temperature Curves and Rating of Electrical Machinery" read at the same meeting by Mr. Rudolph Goldschmidt, both papers containing illuminating information on the subjects discussed.

The writer agrees with the sub-committee report in regard to heating of commutators, but would point out that the commutator connections of many machines, especially those of generators direct-connected to low-speed engines, and even on many motor-generator sets and synchronous converters, are of such length that the nature of the armature insulation can be happily ignored in placing limits on commutator heating.

When carbon brushes were first introduced on machines which had previously been supplied with copper brushes, commutator radiating surface was restricted and the temperature rise of 55 deg. cent. on the commutator was usually guaranteed and accepted, and proved satisfactory.

The recommendation of the sub-committee in regard to bearings is endorsed, and it is particularly pointed out that bearings, and bearing oil, can be operated at much higher temperatures than generally supposed. High temperatures are practically essential to the operation of high-speed turbine bearings, as the friction decreases with increase of temperature. With properly designed bearings and suitable oil and oiling system 100 deg. cent. may be considered a perfectly safe temperature limit.

The fields of maximum-rated turbo-alternators are so designed that if 50 per cent overload at standard fractional power factor is applied the voltage must fall below normal. This is desirable, as otherwise there will be a tendency to damage the machine from overloads. The writer suggests that the "reason to be" of the 50 per cent overload stipulation and its period are debatable. It would seem desirable to allow this overload to permit the starting of additional machines, in case of sudden and unexpected demand for extra current such as occurs in certain localities

from a sudden thunder-storm or fog. He questions if 60 seconds is quite sufficient; 2½ or 3 minutes would seem more appropriate.

The absence of overload guarantees except as suggested above is exceedingly appropriate with modern high-speed machines, particularly of moderate voltage, as the rapid movement of air notably reduces the thermal "surface drop" and makes possible the comparatively high loading of the copper conductors. Conditions, however, are different on comparatively low-speed machines, such as for direct connection to steam engines, gas engines and low-speed waterwheels. Here the surface drop is not reduced to the same extent and consequently for continuous operation the conductors cannot be given the same loading and, therefore, have a considerable reserve of thermal capacity so that it would be appropriate to discuss short time overloads, say of half an hour, or an hour.

The writer endorses the Committee's recommendation to rate alternating-current generators in kilovolt-amperes rather than in kilowatts. He would, however, point out that many turbo-alternators have their capacity limited by the field, and that, as even at 80 per cent power factor the field current for kilovolt-ampere rating has not reached maximum value, the power factor should always be specified. The field current at power factors varying from 100 to 0, (kv-a. remaining constant) for three typical turbo-alternators, is indicated by the following table:

	Power Factor	Field Amperes
Example I:	100 per cent	103.2
	90 " "	122.9
	80 " "	129.2
	60 " "	136.8
	0 " "	143.5
Example II:	100 " "	85
	90 " "	101.3
	80 " "	106.9
	60 " "	113.0
	0 " "	118.5
Example III:	100 " "	61.3
	90 " "	73.5
	80 " "	77.5
	60 " "	82.0
	0 " "	86.5

Synchronous converters are susceptible to additional heating from wattless currents, and when intended for use in part as synchronous condensers the requirements should be carefully specified.

Philip Torchio (communicated after adjournment): In conformity with the understanding at the meeting of February 26 that certain parties should submit in writing their further comments on the proposed revision of rules and rating, I beg to state the following:

There seems not to have been any substantial difference of opinion upon the question of substituting a single rating in place of a normal load rating with overloads, provided the rating were sufficiently conservative. From the discussion at the meeting it developed that there is a substantial discrepancy in the recommendations of the two sub-committees.

Messrs. Steinmetz and Lamme's committee recommended "a maximum rise of temperature of 50 deg. cent. by *conventional methods* of measurement or 60 deg. cent. at the *hot spots*," the difference of 10 deg. cent. being due to temperature grading in insulation. On the other hand, the committee on revision of rating recommended "a maximum rise of 50 deg. cent. at the *hot spots*," which, in accordance with the previous report, would be equivalent to 40 deg. cent. rise by *conventional methods*.

As everybody seems to agree that this difference of about 10 deg. cent. between conventional measurements and actual temperature at *hot spots* (temperature grading) is about representative of actual conditions, and as it appeared from the discussion that it is almost impossible, except for a very expert engineer, to locate the *hot spots*, therefore, I do recommend that the *conventional methods* of measurement be retained and that 40 deg. cent. be the maximum rise of temperature allowable by *conventional methods* and 50 deg. cent. at the *hot spots*.

In other words, the standard rating should be based on *conventional methods* of measurement of temperature, as the ordinary customer would not be in a position to check the rating of his apparatus if the *elusive hot spots* are to be the basis of rating.

In conclusion, I therefore recommend that, to safeguard the interests of the general consumer of electrical power, the Institute's standard rating be based on 40 deg. cent. rise above room temperature, the measurements to be made by any of the present *conventional methods*, also that the machine is to operate at any room temperature up to 50 deg. cent. without making any temperature correction in determining the rise and that $50 + 40 = 90$ deg. cent. be the maximum total temperature at which machine be operated.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

NOTES ON INTERNAL HEATING OF STATOR COILS

BY R. B. WILLIAMSON

In the design of alternating-current generators, close inherent regulation was formerly considered desirable, and the output was frequently limited by regulation, rather than by heating. However, with the general introduction of automatic voltage regulators, close regulation has become less important, and for some classes of generators it is now recognized that it may even be very undesirable. This is so in high-speed machines of large output, in which low reactance is undesirable on account of the excessive current set up in case of accidental short circuit. The tendency is therefore towards machines having relatively poor inherent regulation, and the limiting output of such is fixed by the allowable temperature rise. It is also becoming common practise to rate generators, particularly those for connection to steam or water turbines, on a maximum basis; usually on the output that can be delivered continuously with a maximum temperature rise of 50 deg. cent. The tendency is to place the heating limit at the maximum point to which the machines can be operated safely for continuous service, thus getting the maximum output possible from a given investment in generating machinery.

Assuming the limit of output to be fixed solely by heating considerations, the question arises as to what maximum temperature is allowable, and to which part of the machine it should refer. Rotor coils on a-c. generators can, if necessary, be insulated safely to withstand maximum internal temperatures as high as 150 deg. cent. by using mica, asbestos or similar material. The excitation voltage is not high and the coils are usually of such shape that this kind of insulating material can be applied in such

manner as to make a good mechanical job. With stator coils it is often difficult to use these materials by themselves on account of the relatively high voltage and also because of the irregular shape of the windings. Hence stator coil insulation, in most cases, contains more or less cellulose material, such as cotton tape, treated cloth, etc. Opinions differ as to the maximum temperature at which such material can be operated continuously without deterioration, but a maximum ultimate temperature of 100 deg. cent. in the hottest part may be taken as the limit. It should be noted in passing that metal parts of a generator, not in contact with the coils, as for example the back of the punchings, pole tips, etc., might attain a temperature considerably in excess of 100 deg. cent. without endangering the machine in any way.

Assuming the limit of output to be such that no part of the stator insulation shall exceed a certain temperature, it is important that the designer should be able to make a reasonably accurate estimate of the maximum temperature. Thermometer measurements on machines under test give the temperature of the outside of the coils and the surrounding parts. Measurements of temperature by resistance give the average temperature of the copper but do not give the maximum temperature unless the coil happens to be heated uniformly throughout its length. In machines having narrow cores, measured parallel to the shaft, considerable heat will flow along the copper to the projecting ends of the coils, which are usually cooler than the part in the slot. On the other hand, in machines such as turbo-generators and high-speed waterwheel units of large output, having very long cores, a much smaller proportion of this heat will pass from the part of the coil located in the middle of the machine out towards the ends. Consequently most of the heat liberated from the copper in the slot in the central part of such machines, should be considered as passing through the insulation into the immediately surrounding parts. The highest temperature will thus be on the copper inside the coil and near the central part of the generator. This temperature cannot be measured by taking the increase in resistance of the whole winding, and it is neither safe nor advisable to use temperature coils inside the insulation of the windings on account of the danger of insulation breakdowns and also risk in taking observations. These temperature coils would be directly in contact with the high-voltage winding, and therefore a source of danger under regular operating conditions. However, the temperature of the surrounding parts immediately outside the coil is easily obtained

by thermometers or temperature coils, and if the temperature difference between copper and iron can be calculated, the safe operating temperature for the outside of a coil in any given case can easily be fixed.

It is therefore very desirable to have some means of predetermining this temperature difference, provided the method can be depended upon to give results close enough for the purpose. It is with the object in view of bringing out discussion and results obtained by others that the following is offered.

The temperature difference between the copper inside a coil and the medium with which the outside is in contact, depends on the rate at which heat is transmitted per unit area of insulating wall, the thickness of the wall, and the heat-conducting properties of the insulation. A knowledge of the heat conductivity of various kinds of insulation as used in generators must therefore form the basis of calculation of this temperature difference. Table I shows average values from tests made by Mr. T. S. Allen, and used by the writer, during the past two or three years. Tests on various materials have been recently published by Mr. H. D. Symons and Mr. Miles Walker[1], and some of their results are given in Table II.

It will not be necessary for the present purpose to describe in detail the methods used for measuring the thermal conductivity of the different materials, except to state that, in general, a given amount of power was passed through a known area of insulating material and the difference in temperature between the two sides of the wall observed. The specific thermal conductivity was then expressed in watts per square inch per one deg. cent. difference in temperature per one inch (2.54 cm.) thickness of wall. This conductivity coefficient is here denoted by k_t. It was found in the tests by Messrs. Symons and Walker that cellulose materials, such as cotton, paper, etc., had a considerable temperature coefficient. For example, the conductivity at 100 deg. cent. was about 12 per cent higher than at 30 deg. cent. On the other hand, the heat conductivity of mica was found not to change between 20 deg. cent. and 100 deg. cent.

Assuming that, within the range of thickness used for slot insulations, the temperature difference is directly proportional to the thickness of wall, Fig. 1 shows the relation between watts per square inch transmitted through the insulation, and tempera-

1. Harold D. Symons and Miles Walker, *Journal I. E. E.*, Vol. 48, May 1912.

ture difference for one-inch thickness. It is to be expected that the values of k_t will vary considerably for different samples of similar material, but Tables I and II show that, even though the tests were made by different observers by somewhat different methods, and on materials that doubtless varied considerably, the results agree quite well. With a sufficient number of tests

TABLE I

Description	Value of k_t Watts per sq. in. per 1 deg. cent. per 1 in. thickness
1. Horn fiber	0.00186
2. Fish paper	0.00175
3. Empire cloth (not impregnated)	0.00362
4. Empire cloth (impregnated)	0.00432
5. Flexible mica (not impregnated)	0.00207
6. Flexible mica (impregnated)	0.00255
7. 11,000-volt insulation (mica and empire cloth not impregnated)	0.00318
8. Same as 7, impregnated	0.00432

TABLE II

Description	Value of k_t Watts per sq. in. per 1 deg. cent. per 1 in. thickness
(Symons and Walker.)	
1. Varnished cloth tightly wrapped	0.00634
2. Presspahn untreated	0.0042
3. Rope paper untreated	0.00292
4. Rope paper treated with Sterling varnish	0.0042
5. Fullerboard varnished	0.0035
6. Empire cloth and mica—alternate layers tightly wound	0.0053
7. Empire cloth, mica and tape containing air spaces (see test on turbo-generator referred to)	0.0037
8. Built up micanite tube with about 19 per cent shellac	0.0026
9. Built up micanite tube with about 11 per cent shellac	0.0031
10. Solid mica plate	0.00915

on a given class of material, there should be no difficulty in obtaining the value of k_t closely enough for the purpose in view.

Fig. 1 shows very plainly the relatively poor heat conducting properties of air. For still air the value of k_t may be taken as 0.00052. Thus a layer of air one mil thick may retain the heat as much as 10 mils of insulation. The great importance

of excluding air from the insulating wall and the desirability of a snug fit between the coils and iron are apparent. In estimating the temperature difference between copper and iron, any air spaces present must be allowed for in determining the heat conductivity of the wall as a whole.

The effect of minute air spaces is also shown by the tests on the various materials. The sample of solid plate mica showed a high conductivity, while various kinds of built-up mica had relatively low conductivity. Empire cloth (oiled cambric) is much better than mica as a heat conductor, principally because the small air spaces are well filled with varnish. In every case, im-

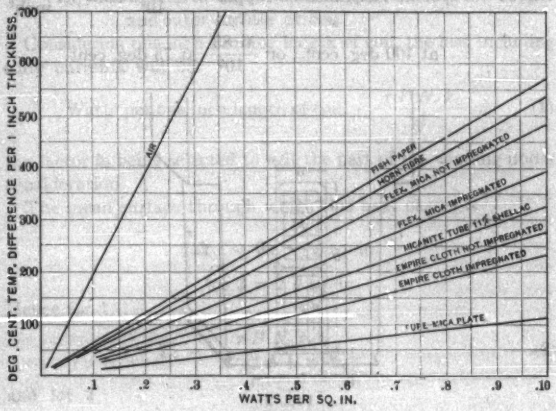


FIG. 1

pregnating a sample improved its conductivity, the increase in some cases amounting to 25 per cent, on account of elimination of air spaces.

With a knowledge of the conducting properties of the various materials making up a given insulation, together with the thickness of the layers, including such air clearance as may be present, a value of k_t for the composite wall can be determined. Considering a slot section as in Fig. 2, we will assume that this one inch running length of imbedded coil is located in the center of the machine and that all the heat liberated in the copper has to find its way out through the insulation to the immediately surround-

ing iron parts. That is, we will assume the worst conditions found in a long machine where little heat can pass from this part to the projecting ends of the coils. In a two-layer arrangement as shown in Fig. 2, the heat liberated in 2 may be different from that in 1 on account of the difference in eddy current loss.[2] Also the surface through which the heat passes to the iron is greater for 1 than for 2, since 1 has three faces in contact with the iron, while the other has but two. The face of 2 next to the insulating wedge will not be considered, since the wedge is usually a very poor heat conductor and has considerable thickness.

Let r = specific resistance of copper $= \frac{0.895}{10^6}$ ohm per $\frac{\text{inch}}{\text{inch}^2}$

at 100 deg. cent., or $\frac{0.83}{10^6}$ at 75 deg. cent.

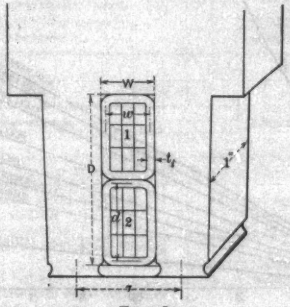


FIG. 2

A = cross-section of conductor in sq. in.

I = current in conductor—amperes.

N_c = number of conductors per half slot = number of turns per coil in Fig. 2.

N = number of conductors per slot.

k_e = factor by which eddy $I^2 R$ loss is to be multiplied to allow for eddy currents.

k_i = thermal conductivity of insulating wall including air clearance (watts per sq. in. per deg. cent. per one inch thickness.)

t_i = thickness of insulating wall in inches measured from copper to iron and including clearances.

2. A. B. Field, TRANSACTIONS A. I. E. E., 1905, Vol. XXIV, page 761.

K = ampere conductors per inch of stator circumference.
W = width of slot.
D = effective depth of slot (not including retaining wedge.)
S = current density in conductor, amperes per sq. in.
τ = slot pitch in inches.
w = mean width of coil in inches measured to center of insulation.
d = mean depth of half coil measured to center of insulation.
T_d = difference in temperature, deg. cent., between copper and outer surface of coil.

Considering one inch running length of coil, the loss including eddy currents will be

$$\text{Watts per one inch length of coil} = \frac{r\, I^2\, N_c\, k_e}{A} \tag{1}$$

the factor k_e being selected to suit the part of the winding under consideration.

The mean surface through which this heat passes is

$$\text{for } 1 = 2\,d + w \text{ sq. in.}$$

$$\text{for } 2 = 2\,d \text{ sq. in.}$$

Hence for 1

$$T_d = \frac{r\, I^2\, N_c\, k_e\, t_i}{A\ (2\,d + w)\, k_t} \tag{2}$$

and for 2

$$T_d = \frac{r\, I^2\, N_c\, k_e\, t_i}{2\,A\ d\, k_t} \tag{3}$$

$\frac{I}{A}$ = current density in stator conductor (amperes per sq.in.) = S

Hence (2) and (3) may be written

$$T_d = \frac{r\, I\, S\, N_c\, k_e\, t_i}{(2\,d + w)\, k_t} \tag{4}$$

$$T_d = \frac{r\, I\, S\, N_c\, k_e\, t_i}{2\,d\, k_t} \tag{5}$$

For most cases it will be sufficiently accurate to treat the slot and coil as a whole and take the area through which the heat passes as $2D + W$. The temperature difference then becomes

$$T_d = \frac{r\,N\,I\,S\,k_e\,t_i}{(2\,D + W)\,k_t} \tag{6}$$

In high-voltage machines using a small conductor, or in others where the design is such as to limit eddy currents to a small amount, the factor k_e can be omitted.

In (6), $N\,I =$ ampere conductors per slot $=$ ampere conductors per inch $\times$ slot pitch, and

$$T_d = \frac{r\,K\,\tau\,S\,k_e\,t_i}{(2\,D + W)\,k_t} \tag{7}$$

It is interesting in (7) to note the various items on which the temperature difference T_d depends. For a generator of specified voltage and with given insulating materials available, the values of t_i and k_t are practically fixed within rather narrow limits. The designer must therefore proportion the slots and fix the current density S in relation to the specific loading K in such manner that T_d will be within the allowable limits. The permissible value of T_d will depend on the ultimate temperature of the surrounding parts. Thus for a maximum internal temperature of 100 deg. cent. and a maximum rise on the iron of 50 deg. cent., the outside coil temperature would be 75 deg. cent. with surrounding air at 25 deg. cent.; T_d in this case therefore should not exceed 25 deg. cent.

On the other hand, if the design is such that the temperature rise on the iron is only 40 deg. cent under these conditions, T_d could be 35 deg. cent. for the same internal temperature of 100 deg. cent.

In (7) it should be noted that the smaller the slot pitch τ the lower will be the value of T_d, other things remaining constant. That is, the more the winding is subdivided the better the conditions are as regards internal heating. However, there is a limit to which subdivision can be carried without making machines unduly large and expensive, and unfortunately this is specially the case in high-voltage generators where the thickness of insulating wall is relatively large. The internal heating of high-voltage

coils thus becomes a difficult matter to handle, especially in large turbo-generators, and it is frequently desirable to wind such machines for lower voltage and use step-up transformers. In high-voltage units, the value of T_d may be surprisingly large if care is not taken to keep the current density and specific loading within such limits that the area of insulation in contact with the iron can transmit the heat without excessive temperature difference.

As regards the values of T_d obtained by the method here outlined, tests, so far as they have been made by the writer, indicate that the calculated difference can be depended on within limits close enough for the purpose. The calculations regarding this temperature difference are also very useful in comparing the merits of different designs.

In one case a 6000-kw. waterwheel generator having a core 36 in. (91.2 cm.) long was tested as follows. A temperature coil was placed in contact with the copper before the stator coil was insulated. This temperature coil was placed at the center of the machine and in the part of the stator coil lying in the top of the slot next to the inner periphery of the stator. Another temperature coil was placed outside the insulation so that the difference in the readings allowed the value of T_d to be determined. The machine was run on short circuit at about 25 per cent current overload until temperatures became constant. Under these conditions, the two temperature coils indicated a temperature difference of 19.5 deg. cent. The insulation consisted of a combination of mica and empire cloth, the value of k_l being 0.003. The various constants in this case were as follows:

$$r = \text{(for 75 deg. cent.)}\ \frac{0.83}{10^6}\ \text{ohms}$$

$$I = 470 \quad S = 1675 \quad N_c = 2 \quad k_e = 1.05$$

$$t_i = 0.15 \text{ including clearance.} \quad d = 1.62 \text{ in.} \quad k_l = 0.003$$

From (5)

$$T_d = \frac{0.83 \times 470 \times 1675 \times 2 \times 1.05 \times 0.15}{2 \times 1.62 \times 0.005 \times 10^6} = 21.1 \text{ deg. cent.}$$

or 1.6 deg. cent. higher than the observed temperature difference.

In the tests by Messrs. Symons and Walker, already referred to temperature coils were placed in a 5000-kw. turbo-generator and the observed value of T_d was 20.6 deg. cent. between copper and iron in the slot. The loss per inch (2.54 cm.) length of coil was 2.26 watts, making due allowance for eddy currents. The mean area through which the heat passed was 5.3 sq. in. (34.2 sq. cm.), thus giving 0.427 watt per sq. in. (0.066 sq. cm.). The thickness of insulating wall was 0.177 in. (4.5 mm.) and k_i thus works out at 0.0037, which checks very well with the values found for similar material when tested in the form of samples.

The writer has other tests on machines at present under way, but these will not be completed in time for the present discussion As mentioned above, the problem of internal heating is of most importance in long high-voltage machines such as turbo-generators. In case the imbedded part is insulated with mica or similar heat-resisting material, or if fabric material in combination with the mica is used simply as a binder and not depended on for insulation, a maximum internal temperature of 150 deg. cent. might be allowable. With a maximum rise of 50 deg. cent. on the iron, and with air at 25 deg. cent., this would allow a value of T_d as high as 75 deg. cent. for this class of insulation. In any event, no matter what kind of insulation is used, or what the allowable value of T_d may be, it is highly desirable that the internal temperature be predetermined as closely as possible and limited to such value that deterioration under long-continued heating will be avoided.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913, By A. I. E. E.

MEASUREMENT OF TEMPERATURE IN ROTATING ELECTRIC MACHINES

BY L. W. CHUBB, E. I. CHUTE AND O. W. A. OETTING

INTRODUCTION

In some late papers* it has been pointed out that it is not the rise of temperature, but the ultimate temperature to which the insulation of electric machines may be subjected, that is the real limitation in the operation of such machines. Therefore, in the measurement of temperatures of electric machines, it is the temperature to which the insulation is subjected, and not that of the copper and iron, which is desired.

In most cases, direct measurements of the temperature of the insulation in the hottest portion of the machine are practically impossible; in order to obtain reliable results of such temperatures, it is necessary to measure some adjacent temperatures and from these derive the desired results. The accuracy of such tests will depend, of course, upon the temperature measuring device, its nearness to the point to be measured and a knowledge of the temperature gradient between the point measured and the point at which the temperature is desired. In estimating the temperature gradient, it is necessary to consider the sources of heat, the direction of flow, and the thermal constants of the conducting parts which affect the distribution of heat.

In electric machines the temperatures of the two faces of any of the insulation will be very nearly the same as that of the adjacent parts, and the temperature of this intervening insulation will be between these limits (except in rare cases of high dielectric losses). For example, the insulation on an armature

*C. E. Skinner, *Proceedings* Association of I. & S. E. E., Oct. 1912.
B. G. Lamme, TRANSACTIONS A. I. E. E., page 21, this volume.

coil will have the local copper temperature on one side and the local iron temperature on the other side. One or the other of these may be the higher, depending upon the relative losses in the iron and copper, the ventilation, and the conductance of the adjacent paths of heat flow. If at all points throughout the length of the slot the iron is hotter than the copper, then the hottest point of the insulation can be measured directly by means to be described later. If the copper at any point is hotter than the iron, it is fair to assume that the hottest coil insulation is next to the copper at the center of the slot. The temperature measurement that can be taken is on the outside of the coil at the center of the slot, and to obtain the maximum temperature of the insulation it is necessary to make allowances for the temperature gradient through the insulation.

Obviously the ordinary methods of measuring temperatures give no exact indication of the distribution of the heat inside of electric machines. Heretofore special methods of measuring temperatures have been considered impractical and almost impossible. Recent developments, however, show that internal temperatures of electric machines can be readily obtained, especially those of stationary parts.

Present Standard Methods of Measuring Temperatures

1. *By Thermometers.* This is the most common method in use. Its chief recommendations are its availability, simplicity and cheapness. Its usefulness is limited to the temperature measurement of the external parts of a machine. Consistent results can be obtained by this method, provided the conditions under which it is used remain the same. On these conditions depends entirely the proper interpretation of the results, for any conclusion based on past experience is reliable only in so far as the basis of that experience remains unchanged. Wide variations in temperatures will be obtained, depending on the location of the thermometers and the method of application to the part in question. Sluggishness is an inherent characteristic and must be kept in mind in any application of thermometers. These limitations will be discussed further under methods of applying thermometers.

2. *By Rise of Resistance.* This method is applicable only to the windings of the machine and obviously represents only an average result, not distinguishing the hot portions from the cold. For windings of high resistance, such as field coils, fairly good

results may be obtained by this method. Although the resistance measurement does not represent the hottest part of the coil, since there is a temperature gradient from the center of the coil to the outside surface, yet in most field coils this gradient will not be excessive, so that the average temperature, while below the maximum, will still be a close indication of the safety of the coil.

In the case of low-resistance windings the results obtained are far from satisfactory. In the first place, laboratory methods and apparatus are required to obtain results with any degree of reliability. Variations of contact with temperature are continually entering in, offsetting the accuracy of even the most reliable measurements. The proper interpretation of correct measurements here is much more difficult than in the case of field coils of high resistance. With the winding passing through several zones of temperatures, the average value of the temperature is but a slight indication of what may be existing in the various parts. For instance, if the end windings of an armature are well ventilated so that the temperature of part of the end copper is but little higher than that of the air, there may be a small portion of the coil buried in the core which is at a considerably higher temperature, and yet have but little influence on the total resistance of the winding. Again, a portion of the end windings may be so packed together and so completely covered by bands, that the relative temperature rise in this part is high, while the armature core and the buried copper is at a relatively low temperature. This condition was brought rather emphatically to the attention of some of us in the case of a large revolving-field generator. The rises by resistance on the various tests were consistent and bore a reasonable relation to the thermometer temperatures, the maximum value being 45 deg. cent. However, on opening the windings it was found on several of the coils that the insulation surrounding the portion buried in the bottom of the slot had been heated to a much higher temperature than that indicated by the rise of resistance method.

Perhaps the most unsatisfactory results obtained by this method are those pertaining to the windings of the armatures of direct-current machines. Temperatures thus obtained are inconsistent and the least said about them the better.

Special Methods of Measuring Temperatures

1. *By Exploring Coils* (Resistance Type). This method of measuring temperatures depends on the fact that resistance of

most materials varies with the temperature of the material. There are several methods in use for measuring the resistance of such coils, any one of which gives results with a fair degree of accuracy. Most of these methods have many complications which are liable to involve inaccuracies. There have been special indicators devised, however, that enable these measurements to be made directly and with very few complications. Bulbs of special forms (suitable for various applications) are manufactured and may be inserted at any point where it is desired to measure temperature. These bulbs are made with either three or four leads which connect to suitable binding posts on the indicators. The indicators have a variable resistance which is adjusted until the galvanometer of the indicator reads zero. This variable resistance is adjusted and calibrated so that the temperature is read off directly from the scale on the indicator. The whole apparatus is convenient for reading temperatures quickly and accurately.

The chief drawback of this method is the expense of the exploring coils. For high temperatures, platinum resistance coils are used, and for lower temperatures, coils of nickel wire. These coils must all be carefully adjusted and calibrated. Likewise the same leads must always be used in conjunction with a certain exploring coil; so that if these leads are broken or if it is necessary to increase the length of the leads, the calibration of the instrument is changed and the correct temperature cannot be obtained unless a new calibration of the coil is made. To obtain a coil of small size, such as must be used within the slot of an electric generator, a considerable amount of fine wire must be used to obtain the necessary resistance. This makes the exploring coil frail and is apt to cause breakage.

2. *By Thermocouples.* Another convenient method of measuring temperatures is by means of thermocouples. This method is used largely in high temperature measurements where thermometers cannot be used. However, it has not been applied in low temperature measurements to any great extent because, until recently, there were no readily portable indicating instruments sensitive enough to give accurate results without troublesome corrections or special adjustments of the thermocouples. To obtain temperatures by this method the e.m.f. of the couple may be measured by a millivoltmeter or by the potentiometer method. This latter method is very accurate and can be used in portable form to read temperatures to a higher degree of accuracy than the ordinary thermometer. Fig. 1 shows a diagram of con-

nections of the instrument which was used in all the tests to obtain the data of internal temperatures which are given in this paper.

B is an ordinary dry battery supplying a very feeble current to the potentiometer circuit made up of the potentiometer wire *P*, a variable resistance R_v, and the resistance *R*. *S* is a special rocker switch with spring so made as to be connected between *a* and *g* on one side and *c* and *h* on the other, when neither side of the rocker switch is depressed. If the switch is depressed on side *g*, connection is made between *g* and *b*. This causes a current to flow in the circuit made up of galvanometer *G* and resistance R_s. The deflection on *G* gives a measure of the current in the potentiometer wire *P*. The resistances *R* and R_s are so adjusted and the galvanometer *G* is so calibrated that the current is at the proper value when the needle of the galvanometer reads the micro-

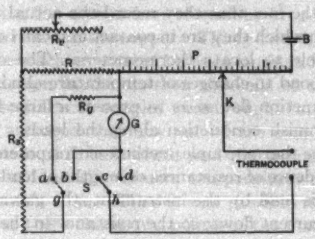


FIG. 1

volts per deg. cent. for the couple that is used in measuring the temperature. With the current set at this value the spring contact again connects *a* and *g* when the rocker switch is released. This connection substitutes R_s for the galvanometer *G*; and since R_s is made equal to the resistance of *G*, the current in the potentiometer wire *P* remains unchanged.

Now to obtain the temperature on the thermocouple, the other side of the rocker switch is depressed, which connects *d* and *h*. This puts the couple, the galvanometer *G*, and a part of *P* in series (the couple being so connected that its e.m.f. "bucks" that of *P*). Contact *K* is run along the drum holding the potentiometer wire *P* until galvanometer *G* reads zero. The result is read off on a scale along the wire *P*, which scale can be calibrated either in millivolts or some arbitrary unit. If a couple is

used that has a linear calibration curve between temperature and e.m.f., the wire P can be calibrated directly in degrees of temperature. A couple made up of steel and advance wire gives a calibration curve that is practically a straight line up to temperatures well above those obtained in electric machines.

The accuracy of this method depends on the sensitiveness of galvanometer G and the length of the scale divisions on potentiometer wire P. The unipivot galvanometer is very satisfactory for this work, giving a meter that is portable, at the same time beng extremely sensitive. The calibration of the potentiometer wire can be made very accurately by using a large number of turns of wire wound around a drum. With the instrument used in this test, seven turns of wire give a range of 150 deg. cent. and each graduation on the scale indicates to two-tenths of a deg. cent.

The great advantage of these thermocouples, like the exploring coils, lies in the fact that they record the actual temperature of the body with which they are in contact and can be applied where it is impossible to locate thermometers. The couples can be made to respond to changes of temperature almost instantly by rolling the junction flat so as to present a large heat-absorbing area and diminish conduction along the leads. A large factor in favor of the thermocouple method with a potentiometer is the utter independence of resistances or lengths of leads; for when the temperature is read by the instrument, the galvanometer reads zero and no current flows; so the resistance in the circuit has no effect whatever.

One thing is quite needful in this method, however, and that is a sensitive galvanometer. The e.m.f. of the couple is small, especially for low temperatures; so to get accurate results, the galvanometer should be sensitive enough to respond quickly to small changes of e.m.f. Another precaution necessary is to see that the material of the couple wires is uniform. It is safe, however, to assume that all the wire on a small reel is of uniform structure, and only one calibration is necessary for each reel.

The use of thermocouples (likewise, resistance exploring coils) cannot be recommended for taking temperatures on revolving parts during the rotation of that element. To take such temperatures it is necessary to use slip rings and brushes. The number of such couples is limited by the space available for the slip rings. The mechanical equipment necessary, especially on machines of high peripheral speed, makes the test extremely expensive, and the results obtained are so questionable that this test cannot be

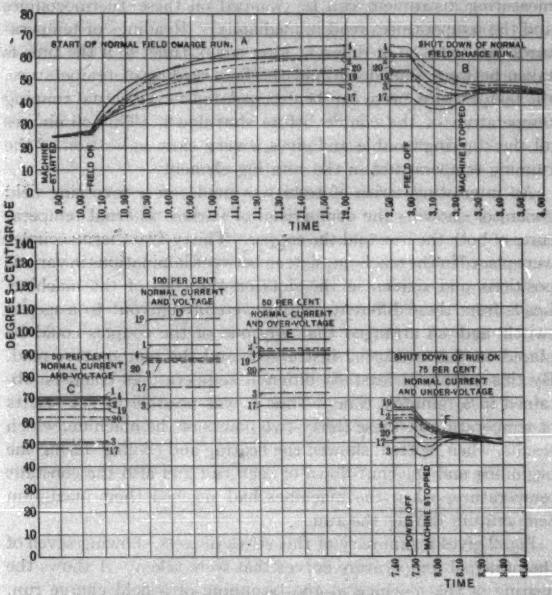
recommended. A better method is to fasten thermocouples on the rotating element at different places where the temperatures are desired, allowing the leads to be exposed in some places where there will be no interference with the rotation of the machine. On the shut-down of the machine, leads from the measuring instrument can be clamped on these thermocouples and the temperatures read immediately. Readings of temperatures can be taken at different intervals of time; so if the time is taken between shut-down and the first reading of temperature, the temperature curve can be exterpolated to the actual running temperature of the couple before shut-down. This eliminates all the slip ring trouble and gives a very close indication of the running temperatures in the rotating element.

An interesting series of tests was made on a revolving field generator, showing the comparison of various internal temperatures of both the iron and the copper. Thirty-two thermocouples were placed in the machine; sixteen between laminations in various positions and sixteen in the slots on the coils of the machine. Leads from these different couples were brought out to a special switch and so arranged that any one of the couples could be placed on the measuring instrument and the temperature read. By this means, at least six different temperatures could be obtained in a minute's time. Thus it was possible to get results of temperature at these thirty-two points of the machine, which results, when plotted, showed the heating and cooling during the beginning and the shut-down of each run and also the constant temperatures when the machines had reached their maximum temperature during the run.

Fig. 2 gives a summary of this series of tests, showing seven of the principal temperature curves that were taken. *A* shows the heating of the machine at the beginning of a field charge run. Of course, it is reasonable to suppose that the laminations will become hotter than the coils in a run of this nature. *B* shows the shut-down of this test. When the field was removed from the machine, there was no braking effect to stop the rotating except the friction of the bearings and the windage, and the friction of the brushes on the commutators of two driving motors. It is interesting to note the various temperatures. Couple No. 17, located between a coil and a wedge, cools until the rotation almost ceases; then it becomes warmer again, because the ventilation due to the rotation ceases and the hotter parts of the machine warm the air in the gap, which causes the temperature of couple

No. 17 to rise. This effect is shown also to a lesser degree on No. 3, which is near an air duct in the iron.

C, *D* and *E* of this figure show the maximum temperatures of several other tests. *F* shows the machine shut down as in *B*, but



1—In iron 1/2 in. below top of tooth in center of package.
2—In iron 1/2 in. below bottom of slot in center of package.
3—In iron 1/2 in. below bottom of slot next to air duct.
4—In iron 4 in. below bottom of slot in center of package.
17—In slot between coil and wedge.
19—In slot between coils.
20—In slot between side of coil and iron.

FIG. 2

under somewhat different conditions. A load was on during this run and when the power was removed, the field of the machine was reduced to one-half, instead of being removed entirely as in *B*. Thus the rotation was stopped in eight minutes' time, about one-third of the time as required in test *B*. The curves show the

temperature equalizing again in the same manner. These results bring up the question "What is meant by 'shut-down' temperatures?" Obviously very different results would have been obtained on these two tests *B* and *F* if thermometers had been placed on the machine after the rotation had ceased. This point will be discussed later under "Method of Stopping Rotating Element."

Present Standardization Rules Indefinite

1. *Room Temperature.* This term enters into practically all contracts for electric machines and its meaning should be so clear as to be beyond dispute. The temperatures of air foreign to the machine can have no effect on the machine's temperature; it is the air that immediately surrounds a machine that is effective; or in case of machines artificially cooled, it is the temperature of incoming air. Even under these limitations there is still too great a latitude for dispute. Thermometers so placed as to be affected by the outgoing air are even more undesirable than those placed at considerable distance from the machine tested. It seems that there is no absolute rule adaptable for every case, but certain general limitations may be suggested; such as the maximum distance from the machine, which may be expressed in terms of the diameter of the rotating part, or the thermometers must be so located as to indicate either the temperature of the still air surrounding the machine or else that entering it. Local conditions frequently demand special consideration, such as the effect of the temperature of poorly ventilated pits on the parts affected. In such a case the average temperature surrounding the machine is as foreign in its effect on the local parts as that of the north pole on the equator. In the case of a certain 8770-kv-a. generator in a large hydroelectric plant, this local effect was as much as 10 deg. cent. In another case, safe limits were far exceeded until the pit was properly ventilated, when the temperature of the part in question at once became normal.

2. *Method of Applying Thermometers.* As previously stated, the inferences deduced from thermometer measurements depend upon the duplication of conditions. This applies especially to the application of thermometers. The methods used depend considerably on the nature of the temperature to be measured. These may be divided into two classes: those pertaining to stationary parts, and those pertaining to rotating parts.

In the stationary parts, all thermometers may be located before

the start of the test, and as the temperatures increase gradually there is no special difficulty in the thermometer following very closely. In the larger machines, the thermometers should be protected from the windage of the machine, or other drafts, by a small covering. This may be of putty, clay or felt. Some persons prefer one and some another. Putty is rather soft at working temperatures. Clay makes a very good holding medium when carefully put on, but our experience has been that more uniform temperatures, and usually higher results as well, are obtained with the felt. On windings this covering may be in the shape of a small sleeve, the bulb being exposed only on one side; the whole being tied to the coil securely with twine. On iron laminations a small felt pad about 1½ by 1½ in. (3.8 by 3.8 cm.), glued to the surface under which the thermometer is inserted, seems to give the best results. This method also has proved satisfactory when used on the larger copper conductors. The pad must not be too large, as a hot spot may be created, neither must it interefere with the radiation of the machine. On smaller machines, the liability to hot spots becomes much greater and either a very small ball of clay is to be preferred, or else the thermometers should be left bare and treated after shut-down as described below for thermometers on the rotating parts. On these machines a thermometer will not give the correct maximum values while the machine is running, but will indicate when the machine has reached a constant temperature.

The method of obtaining temperatures of rotating parts by thermometers presents quite a different problem. A very wide range of results may be obtained on account of variations due chiefly to the method of getting the heat from the body, whose temperature is to be measured, to the thermometer bulb. The thermometer bulb can be so placed, with respect to the copper in the coil, that the resistance in the heat-conducting path to the bulb is much greater than desirable. For instance, if a thermometer is simply laid on the coil whose temperature is to be measured, and covered with a little waste, and another thermometer is placed on the coil and provided with a seat made of tin-foil, two different results will be obtained. Obviously, with a metal seat, a larger amount of heat in a given time can be conducted from the coil across the insulation and thence to the bulb, than would be the case without the metal seat; for the section of the heat conduction path through the insulation is increased and the average length of the path shortened. However, if the

dissipation of conduction of heat from the point to be measured to other parts of the winding is relatively slow, both thermometers should eventually indicate the same temperature. If, however, the heat dissipation is rapid, either by conduction to the air or to other parts of the winding, the thermometer which gives the quicker reading should reach a higher temperature. In a certain instance it was found that the thermometer provided with a metal seat reached this maximum six minutes before one simply laid on the winding, both being protected from the air in the same manner. The discrepancy in temperature was eight degrees, the cooling curve of the machine in question falling rapidly. Thermometers are sluggish in their action and they take a certain time before they come up to temperature. So in similar conditions as mentioned above, if thermometers are applied which have previously been heated to about the same temperature as the machine, higher results of temperature will be obtained than if the thermometers had not been heated before application to the machines.

Thus, all these methods of applying thermometers will give results that in no way will be comparable. There must be a definite ruling as to the manner of applying thermometers so as to obtain comparative results.

3. *Method of Stopping Rotating Element.* Another point which causes dispute is the method of bringing the rotating element to rest after a temperature run. Should the machine be allowed to rotate without any load until all the flywheel effect is expended, or should the magnetic field be used to retard the machines, or should the machine be braked mechanically by means of pulleys and ropes to stop it more quickly? It is quite evident that the fanning effect of the rotating element lowers the temperature of the machine very rapidly. The curves shown in Fig. 2 show temperatures in a machine which had sufficient flywheel effect to allow it to rotate freely for a period of 22 minutes after the load was removed. It is obvious that considerable variation will result in the temperature obtained if the time of bringing the rotating element to rest is varied. For instance, from the curves of the normal field charge run in Fig. 2, it is seen that there is a considerably greater drop in temperature in the 22 minutes than in five minutes. So if the machine had been stopped in five minutes by mechanical braking, higher shut-down temperatures on the rotating element would have been obtained. In another case when mechanical braking was resorted to, temperatures 10

degrees warmer were obtained when shut down in 1½ minutes than when shut down in six minutes.

Conclusion

It is evident from the foregoing discussion that the proper interpretation of temperature results depends almost entirely upon the conditions of tests and upon the temperature measuring method employed. No one method is suitable in every case. The thermocouple and exploring coil are generally applicable; but the thermometer and rise by resistance methods are preferable in many cases because of convenience, simplicity and inexpensiveness.

The experience of the authors has prompted the following recommendations in regard to taking temperatures of electric machines:

1. Thermometers should be used to measure all temperatures of exposed parts, the temperature of which is constant or is not changing too rapidly for the thermometer to follow.

2. In cases where the part to be tested is small, and the thermometer and covering may disturb the thermal conditions, the thermometer should not be used.

3. The application and covering for thermometer bulbs should be standardized.

4. The rise by resistance method should be used to measure only the temperatures of windings which are known to be at a rather constant temperature throughout, such as transformer coils, field coils, some stator windings, etc.

5. The rise by resistance method should not be used for windings or parts of windings of very low resistance.

6. Thermocouples or exploring coils may be used to measure temperatures of internal parts, especially in machines with long cores, such as high-speed turbo-generators, and also in parts where steep and doubtful temperature gradients make it impossible to draw any definite conclusions from thermometer temperatures or rises by resistance.

7. Exploring coils are either expensive, or require expensive adjustments and laborious calculations for tests. Thermocouples are preferable to exploring coils in commercial testing.

8. If internal temperatures are required in revolving parts, thermocouples may be used and readings taken after shut-down. Running temperatures with slip rings and brushes cannot be recommended.

9. Temperatures which will be affected by the permanent application of a thermometer or a pad may be taken by the momentary application of a quickly responding thermocouple.

10. The rises of temperature should be based on the temperature of the *cooling air*. The determination of the cooling air should be standardized as far as possible.

11. A convenient and probably the best method of stopping a machine after a temperature run, is by field excitation. Whenever possible, full field should be used to stop the machine quickly and thus maintain the temperatures.

It is hoped that more definite rulings can be established in regard to temperature tests. A temperature obtained within a machine by means of a thermocouple or an exploring coil may not meet guarantees as specified in the present Standardization Rules. In addition to specifying the methods to be used, the limiting temperatures must be considered in each case.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913, By A. I. E. E.

METHOD OF DETERMINING TEMPERATURE OF ALTERNATING-CURRENT GENERATORS AND MOTORS AND ROOM TEMPERATURE

BY HENRY G. REIST AND T. S. EDEN

Correct determination of the temperature of apparatus is of great importance to the designing engineer. Of even greater importance, is the determination of a fair room temperature, since all temperature guarantees are made on the basis of rise above room.

The determination of the temperature of apparatus may be made by thermometer, by resistance measurement or in special cases by the use of temperature measuring coils.

THERMOMETER

In the use of thermometers, it is obviously necessary to select the means of applying and covering the bulbs which will give on the one hand the maximum temperature attained and on the other, will not increase temperature of part where the thermometer is applied. Several coverings are available, such as cotton or woolen waste, felt, putty, etc. To determine which of these coverings is the most suitable, the following experiment was recently made.

A copper plate was fitted over the top of a vessel containing water, so that it could be uniformly heated, and the temperature changed as desired. Bulbs covered with different materials were applied to the copper plate and temperatures read over a range from 86 deg. cent. to 32 deg. cent. The following table gives the results.

The temperatures as read across the table herewith, were taken at the same time, and after they had become constant

Covering	Putty 1 in. dia.	Fiber tube 1½ in. dia. Top filled with waste	Felt 2 in. square	Woolen waste 2 in. dia.	Cotton waste 2 in. dia.	Uncovered between preceding	
Temp. deg. cent.	86	78	79	81	82	68	69
	71.5	66	66	68	68	59	59
	62.5	57.5	57.5	60	60	50.5	51.5
	51.5	47.5	47.5	49	49	44.5	44.5
	42	40.5	40.5	40.5	41	38.5	38
	37	35.5	35.5	36	36	34.5	34.5
	32	31.5	31.5	31.5	32	30.5	30.5

These thermometers were then carefully calibrated over a temperature range from 89 to 26 deg. cent and found to agree within one deg. at the higher temperatures and one-half deg. at the lower temperatures. The table shows that the bulb covered with putty gives the highest reading in each case.

It is therefore recommended that putty covering be used as the standard, since it not only gives the highest reading but is convenient to handle and can be applied in a compact form, not covering an unnecessarily large area, which would impede natural radiation.

Resistance Measurement

Measurements of resistance both cold and hot may be accurately taken, but in practise it is found that the temperature *cold* is uncertain.

This is due to a possible or perhaps even a probable difference of average temperature of the winding of which the resistance is to be measured, from that of the measured temperature of the air.

A resistance measurement on an armature winding taken at a temperature below 25 deg. cent. and again at a temperature above 25 deg. cent., when reduced to resistance at 25 deg. cent. will seldom check within 5 per cent. Consequently manufacturers must build with larger margins when required to guarantee temperatures by resistance.

The temperature of windings so determined, is not a gage of the highest temperature attained, but is an average temperature. The temperature of the end windings on an armature will usually be lower than that of the portion of the winding imbedded in the slot; similarly on revolving field windings, the temperature indicated by the *IR* drop, will frequently be found lower than that shown by thermometers applied to parts of the coils, for example adjacent to mechanical supports between coils.

This method of obtaining temperature rise on alternating-current generators and synchronous motors, should be limited to the revolving field windings of those machines which are so enclosed that thermometer application is impossible.

Temperature Measuring Coils

In apparatus such as steam-turbine-driven and large high-speed waterwheel-driven generators, where the stator windings are inaccessible for thermometers, it is possible to determine the temperature of these parts by using small coils of fine wire, non-inductively wound, which may be placed next to the insulated coil in the slot portion or outside, as desired. Accurate measurements of resistance of these coils by voltage drop may be taken, and the highest temperatures attained may be known.

These coils should be calibrated at a known temperature before being put into a machine.

This method may be applied to any machine and will bring to light faulty design. Insulating fabrics, such as oiled linen, varnished cambric, etc., are apt to deteriorate more rapidly than desirable between temperatures of 90 and 100 deg. cent. and consequently apparatus so built should not be permitted to run at these temperatures. Other insulating materials are in use and also in process of development, which will permit of operation at higher temperatures than these. This method is recommended for the investigation of temperatures in factory tests, but customers should not require it on more than one of several duplicate machines, unless they are willing to stand the attendant expense, since thermometer readings would be sufficient to show that two or more machines were alike.

For machines with small slots, this method of determination should not be necessary.

Its field of application should probably be in apparatus of 6600 volts and over, and on machines of outputs above 2000 kw.

A few examples are given to show how the temperature *rises* measured by thermometer, resistance, and temperature coil methods differ on one and the same heat run.

The value of this table is more as a comparison of the different methods of measuring temperature, than an indication of the maximum temperatures in a machine, since the tests were not made under full-load conditions, but under such artificial loads as could be obtained at the time the machines were in test.

Size of generator	Voltage	Thermometer	Resistance	Temperature coil
15000 kw.	9000	27	40	44
8750 kw.	6900	22	26	39
6000 kw.	6600	29	35	39
5000 kw.	4000	19	33	44
4000 kw.	4000	15	27	30
3750 kw.	6600	15	30	33
3750 kw.	6600	19	30	33

This substantiates the fact that internal temperatures are considerably higher than outside temperatures in a machine.

It is hard to form a conception of the internal temperature of a coil by external thermometer reading, since with a given loss per unit of area of surface of the coil, the external temperature is very largely dependent on the rate of flow of the cooling air over the surface, whereas the difference of temperature between the inside and outside is a factor of the rate of transmission per unit cross-section of the material used in insulating and of its thickness.

In the rotors of turbo-driven generators, on account of the construction necessary, temperatures greater than in the stators will result, requiring the use of insulations which will stand such temperatures.

On this part of a machine there appears to be no difficulty in making an insulation safe for these higher temperatures, due to the low potential employed for excitation.

The determination of these temperatures should be by resistance, calculated from the $I\ R$ drop. To apply temperature measuring coils would be extremely difficult and expensive, involving auxiliary collector rings for measuring the resistance and introducing inaccuracies of measurement as compared with coils in a stator.

Room Temperature

Commercial testing must necessarily be conducted in rooms where the temperature will vary and where apparatus and room thermometers will be subjected to air currents caused by opening of doors or windows.

Machines of small volume will respond quickly to changes in temperature of the surrounding air, whereas the temperature change in large machines will lag appreciably behind the change in room temperature.

It is therefore necessary to find some means of lagging the bulbs of thermometers used for determination of room temperature, so that the changes will follow approximately the same curve as the apparatus. For this purpose, a small steel cylinder with a hole in the center, filled with oil in which the thermometer is placed, has been used by some manufacturers.

In order to determine their heat capacity a series of these cylinders was made up, 3 in. (7.6 cm.), 2 in. (5.1 cm.), 1⅜ in. (3.5 cm.), 1 in. (2.54 cm.) and ¾ in. (1.9 cm.) in diameter, all 3 in. (7.6 cm.) high, all provided with a ⅜-in. (0.95-cm.) diameter hole, 1½ in. (3.8 cm.) deep, for the thermometer. They were heated up to approximately the maximum temperature reached by

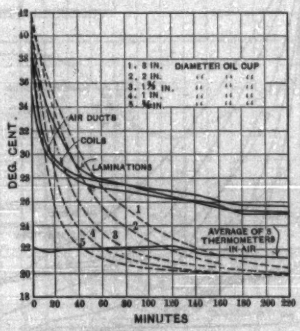


FIG. 1—COOLING CURVE OF 860-KV-A., 2300-VOLT, 720-REV. PER. MIN. 60-CYCLE ALTERNATOR, AND OIL CUPS.

a machine at the end of a heat run, and temperature recorded at frequent intervals, also of the machine running idle. These readings are shown in Fig. 1.

It will be noted that the cooling curve of the 3-in. (7.6-cm.) oil cup, as these cylinders may be called, follows the laminations and the ¾-in. (1.9-cm.) oil cup follows the coils over the higher temperatures recorded, or those temperatures which the machine parts attained under heat run.

Constant temperature of the machine parts is reached at a temperature above that of the room, due to warming up of the air passing through the machine, running at full speed.

It would therefore seem reasonable in determining the room

temperature to use an oil cup 2 in. (5.1 cm.) in diameter, which will follow the average temperatures of the different parts of the machine.

Similarly on a 3750-kv-a. unit, Fig. 2 shows that the cooling curve of the 2-in. (5.1-cm.) oil cup follows the temperature changes of the laminations very closely.

These oil cups, together with thermometers suspended in air, were together with thermometers suspended in air were then

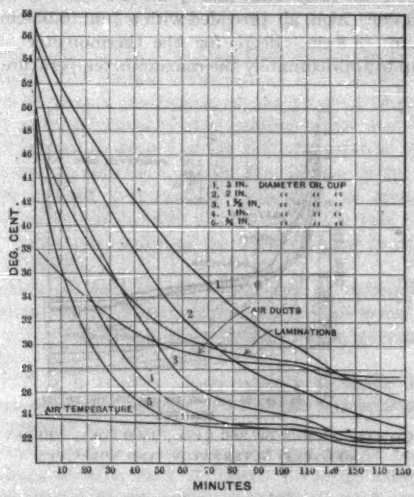


FIG. 2—COOLING CURVE OF 3750-KW., 6600-VOLT, 500-REV. PER. MIN 50-CYCLE ALTERNATOR, AND OIL CUPS.

used in connection with a machine in test, which had reached constant temperatures. Doors were opened for an hour so as to reduce room temperature, and temperatures recorded as shown in Fig. 3.

The following table shows temperature rises above the air-suspended thermometers and above the 2-in. (5.1-cm.) diameter oil cup.

This shows that the temperature rises above the oil cup are fairly uniform and those above the air thermometer vary a great deal.

	Rise over air thermometer	Rise over oil thermometer
Doors opened	28.6	30.2
10 minutes later	33.2	31
10 " "	31.7	31.1
10 " "	29.2	30
10 " "	28.4	29.7 etc.

From these and other observations of a similar nature which have been made, it is recommended that an oil cup of this sort be used for determining room temperatures, both on account of its convenience and accuracy.

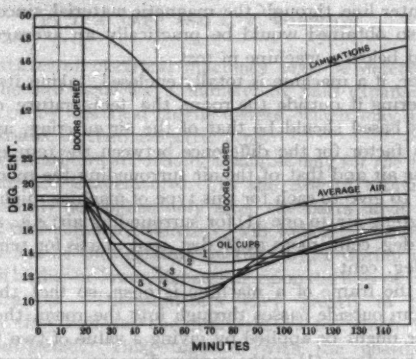


FIG. 3—COOLING CURVE OF 860-KV-A., 2300-VOLT, 720-REV. PER MIN. 60-CYCLE ALTERNATOR, AND OIL CUPS.

It is possible that for stationary apparatus, such as transformers, a satisfactory solution may be arrived at by taking the temperature of an idle machine, the cooling medium being air, water, oil, etc. However, for rotating apparatus, we believe the above method will give reasonably accurate results.

Several different methods of ventilation are used in alternating-current apparatus and the "room temperature" cannot be arrived at in the same way for all cases.

The majority of machines built, take their cooling air from the room they are in and deliver it to the same room. For these, "room temperatures" should be determined in some such manner as given above.

Frequently, with horizontal machines ventilated in this manner, a large part will be below the floor line of a station, in a pit. Unless such a pit is properly ventilated, a portion of the stator will show temperature rises which are dependent on the temperature of the air in the pit, and the rises of such a portion should be based on the pit temperature. It might be noted that the portion so affected will come below the floor line on the one side and above on the other, depending on the direction of rotation. The temperature of the rotor should be referred to an average of the pit and room temperatures, the value of each being decided on the portion of the machine in pit.

For vertical types ventilated in this manner, we would recommend placing the room temperature thermometers at the level of the center line through the magnetic material, since the temperature so obtained would be practically an average of that above and below a machine in test.

However, if a machine is totally enclosed, taking its air from and delivering it outside the room, the temperature on which the rise is based should be that of the air entering, applying a correction factor for the difference between the temperature of the ingoing air and that of the air surrounding the machine. A fair value to give to each for this type of machine might be four (4) for ingoing air, to one (1) for surrounding air: *e.g.* air entering at 15 deg. cent. room at 30 deg. cent.; basis for temperature rise, 18 deg. cent.

Where the frame of a machine is open, so that the air delivered from outside passes through into the room, the correction factor might be applied by giving a value of two (2) to the ingoing air and one (1) to the surrounding air; *e.g.*, air entering at 15 deg. cent. room at 30 deg. cent. basis for room temperature 20 deg. cent.

It would be very difficult to make an exact determination of these correction factors. The above are given as suggestions, which we believe would be fair. Doubtless, many cases will arise which can only be settled on their individual merits.

We appreciate that the tests are not sufficient to base conclusions on and that probably more extended tests will be advisable.

At best, however, the size of oil cup will have to be a compromise because it will not be practicable to change the size of cup for different machines or to use different cups for comparison with different parts of a machine.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

THERMOCOUPLES AND RESISTANCE COILS FOR THE DETERMINATION OF LOCAL TEMPERATURES IN ELECTRICAL MACHINES

BY J. A. CAPP AND L. T. ROBINSON

Temperatures of electrical machines may be determined in either of the two usual ways, namely, by fluid expansion thermometers, or by electrical thermometers, which may be either of the resistance or thermoelectric type.

Fluid thermometers are usually available only for the measurement of surface temperatures. In the case of rotating parts they can usually be applied only after the parts have come to rest. The thermometer, therefore, will indicate a temperature which may not be that existing on the surface during rotation, but may be higher or lower, depending upon the flow of heat during equalization. Thermometers vary greatly in the rate with which they indicate the temperature to which the bulb may be subjected. This, together with the possible error due to the equalization of temperature just mentioned, may bring about considerable errors in the results. Ordinarily the thermometer bulb is held in contact with the surface whose temperature is to be measured, by means of some plastic material, such as putty, which in itself is of relatively low heat conductivity. If the temperature changes which take place during equalization are relatively rapid, there is here a further possibility of error.

Unless some such material as putty is used, the temperature readings of the thermometer will be low, because there is not sufficiently intimate contact between the bulb and the surface whose temperature is to be measured.

As ordinarily supplied by the makers, either mercury or alcohol thermometers are calibrated with either the entire stem immersed

in a liquid or atmosphere at the temperature to be measured, or at least with the stem immersed to the point of indication. In other words, the thermometers are customarily supplied with their scale adjusted for full scale immersion. In use in determining the temperature of a surface, only the bulb, or at most but a short portion of the stem above the bulb, is exposed to the temperature to be measured. There have been worked out formulas for correction for the emergent stem, as it is called, but these are cumbersome, and, indeed, such corrections are comparatively seldom made in ordinary measurements of temperature. The correction for the emergent stem may amount to as much as two to four degrees at 80 to 100 deg. cent., the reading in such case, of course, being low. It is possible to obtain thermometers specially calibrated with only the bulb and a very short portion of the stem immersed in the liquid or hot atmosphere used for calibration. Such thermometers when calibrated with, say, 2 in. (50.8 mm.) immersion, may safely be used under ordinary conditions, where the temperature of the emergent stem is approximately the ordinary room temperature at which the calibration was done. The error due to failure to correct for emergent stem is far larger than the probable error of even the ordinary commercial thermometer when used as calibrated. In fact, such commercial thermometers are readily obtainable with an accuracy of four to five tenths of one degree at 100 deg. cent. Of course the error due to the emergent stem is entirely independent of the inherent accuracy of the thermometer itself.

The second method of measuring temperatures, or the electrical resistance thermometer, is susceptible of a variety of applications. Essentially it depends upon the accuracy with which the coefficient of change of resistance with temperature is known. The simplest and most obvious application of this method is the use of windings of the motor or generator itself. In such case, the material being copper, the temperature coefficient is assumed to be 0.00428 at 0 deg. cent., 0.00386 at 25 deg. cent., and the accuracy of the results obtained is dependent upon whether the actual copper used in the winding has exactly this temperature coefficient.

Commercial copper, such as would ordinarily be used in electrical machines of the kind being considered, would very seldom vary enough from standard conductivity and hence from the temperature coefficients belonging to 100 per cent conductivity

copper to influence the correctness of the temperature determination more than one deg. cent. between the limits of 25 and 100 deg. cent. This question of definitely known temperature coefficient is, therefore, not of importance in temperature determinations using the entire winding, but in resistance thermometers for accurate work, in which prepared coils are used, this small error is easily taken care of.

The error, then, in measuring temperature by resistance of windings, may be considered as governed almost entirely by the ability to determine accurately their resistance. The error is about three deg. cent. for one per cent variation from correct resistance values. When using workshop means for determining the resistance it is reasonable to expect measurements within one per cent and, therefore, the temperature should be known by this means within three or four deg. cent., if the initial temperature and resistance are known. The temperature rise of a winding of a machine determined by resistance measurements is, of course, subject to still further uncertainty due to the difficulty, especially in large machines, of knowing definitely the temperature of the winding when the cold resistance is observed.

The increase in resistance which is used as the measure of temperature corresponds to the average increase in temperature of the entire winding throughout its length, and the results obtained do not indicate the temperature at any part of the winding. There may be large differences in different parts of the same conductor.

Another application of the resistance method of measurement consists in the placing of fine wire coils at any desired location in or about the winding. Such coils may be placed with thin insulation practically in immediate contact with the conductor, or they may be embedded in the insulation at any desired depth. In such case highly accurate measurements are possible, because the actual temperature coefficient of the piece of wire used as the measuring device is easily known. Here again, the increase in resistance is the result of the average temperature rise in the immediate vicinity of the measuring coil. The extent of the coil, therefore, determines the degree to which the temperature reading obtained is local. Such a device, by bringing leads from the resistance coil to collector rings, may be used to measure temperatures while the parts in which the measuring coil is embedded are rotating.

The practical value of resistance thermometers for high temperatures is doubtful. Base metal coils are permanently changed

in resistance by continued heating and if the more expensive platinum windings do not suffer from this cause, they are at least subject to mechanical damage. For the moderate temperatures being considered there is no danger from oxidation and therefore copper or some similar metal may be used, and the coil may be embedded in the machine during construction and thus well protected from mechanical damage, or it can be made up in form, to be inserted later. The temperature coefficient of these coils may be determined with any desired degree of accuracy before they are inserted and the resistance can be measured within any required limits when they are in place. For precision testing it is quite possible to obtain results without difficulty within a part of a degree, using some sort of bridge for determining the resistance; the bridge may be graduated to read directly in temperature. For workshop and central station applications of resistance thermometers, direct-reading temperature-indicating attachments, in the form of indicating switchboard instruments, may be used and satisfactory accuracy obtained. The inserted resistance coils should be reasonably non-inductive and precaution should be taken to have them so protected by insulation that they may not be the cause of damage to the windings of any machine in which they are used, or the means of transferring high tension to the switchboard instruments connected with them or to the low-tension d-c. network which supplies current to operate the device. There can be no question of the reliability of the temperature obtained by this means, representing the average of the region occupied by the coil, but no matter what system of connections is chosen and what safety devices are applied in connection with it, when the coil is embedded in or between high-tension windings it is difficult to dismiss entirely the feeling that an added element of danger to the machine and operator must be reckoned with.

The second electrical method of determining temperature is that using the thermocouple. Since the electromotive force generated by the thermocouple is a function of the difference between the temperature of the junction of the wires forming the couple and that of their free ends, it is obvious that the thermocouple may measure the temperature more nearly locally than any other device.

This same fact requires that there be accurate control of the temperature of the free ends, or the cold end temperature, as it is commonly called. With this temperature controlled by immer-

sion of the free ends in oil or by other equally simple means it is possible to determine the electromotive force with great accuracy, and because of the ease with which a thermocouple may be calibrated for use at relatively moderate temperatures, this method of measurement is a very satisfactory one. One of its most interesting applications is in the estimation of the temperature of the rubbing surfaces of a bearing.

It is easily possible to provide a minute junction with very thin insulation and embed it in the babbitt metal in a bearing, so that it is but a fraction of an inch below the actual surface of the babbitt, and by this means the temperature of the actual rubbing surface of bearings, at predetermined points in the journal, has been measured very satisfactorily. By similar means the temperature of any part of the apparatus may be obtained if the parts are still. Measurements may also be made with the apparatus in operation. In the case of rotating parts, however, it is necessary to provide slip rings of such materials as to avoid disturbing or parasitic electromotive forces. Artificially prolonging the couple in this way permits the control of the cold end temperature and the taking of readings during operation.

For the moderate temperatures encountered in electrical apparatus it is not necessary to go to the expensive rarer metals which are required for similar thermocouples used for pyrometers at high temperatures. Copper with constantan makes a satisfactory couple, yielding a readable electromotive force even with small differences in temperature. In no case, however, with the ordinary differences in temperature to be expected, will any of the thermocouples commonly used yield sufficient electromotive force to permit the use of ordinary switchboard instruments for reading, but instead the measurements must be made by instruments equivalent to galvanometers.

Thermocouples may be calibrated to give accurate indications of temperature, and when used with directly indicating instruments, results within a degree or two may be expected. For more refined work potentiometer arrangements may be applied and by this means any desired degree of precision can be reached.

Of the methods of measurement mentioned, ordinary thermometry is the simplest, quickest, and most easily performed, but it is the least accurate. It is usually applicable only to surface conditions, and can seldom be used to determine anything concerning the internal temperatures of the apparatus. The

choice between the electrical resistance method and the thermoelectric method is largely determined by conditions, and ease of application in the individual case. Both methods, compared with ordinary thermometry, are somewhat more difficult of application and require more delicate apparatus than the ordinary meters used in commercial testing. In rapidity of indication the thermocouple will rank first, if properly applied, though the indications of the electrical resistance thermometer will be nearly as rapid, provided the resistance coil is of right proportions and applied in intimate thermal contact with the parts whose temperature is to be measured.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS AND OF COOLING MEDIUM

BY S. E. JOHANNESEN AND G. W. WADE

Of all measurements applied to transformers, none are so difficult to duplicate and to obtain accurate and consistent results from, as tests for determining temperature rise. There are a great many different conditions to be controlled or corrected for in case of variation. The difficulties are principally due to the four following causes:

1. Variations in load, including voltage, current and frequency.
2. Variations in the cooling medium with regard to its condition, its temperature, and the quantity supplied in case of artificial cooling.
3. Inaccuracies in the measurement of the effective temperature of the cooling medium.
4. Inaccuracies in the measurement of hot temperatures.

The first and second of the above causes are not within the province of this paper, but the other two will be taken up in the above order after a short discussion of the measurement of temperature.

THERMOMETERS

Temperatures are usually measured by means of mercury thermometers, although other types are sometimes used for special purposes.

Mercury thermometers are made for various ranges of temperature and for various degrees of accuracy. Other things being equal, the shorter the range the higher the degree of accuracy. It is desirable, therefore, to select a thermometer having a range just sufficient to include all the temperatures to be measured. For air temperatures a range from about 0 to 50 deg. cent.

is most suitable, while a wider range, say from 0 to 100 deg. cent., is usually necessary for determining hot temperatures. For such ranges mercury thermometers can be made for an accuracy of about 0.01 deg. plus or minus, but these are too expensive and too fragile for ordinary use. The cheapest form has an accuracy of about 1 deg. plus or minus. Mercury thermometers are best suited for the determination of temperatures of air, tanks, and other iron parts. They should not be used in strong magnetic fields on account of the heating due to eddy currents induced in the mercury. It is preferable not to use them inside the transformer case unless the bulb is very carefully protected, since short circuits may be caused by the mercury falling on the coils or leads in case the bulb is broken.

Spirit thermometers are most suitable for obtaining temperatures of coils or oil, as they are not affected by magnetic fields and as no bad results will be caused by their breakage. They are not as accurate or as reliable as mercury thermometers and it is necessary to calibrate them for the condition under which they are to be used in order to obtain correct readings. For instance, one calibrated with a 5-cm. immersion of the bulb in oil would not give accurate results when used totally immersed. With proper calibration, however, they have an accuracy of about 1 deg. plus or minus in the 0 to 100 deg. range.

Capillary tube thermometers are useful for determining temperatures at a distance below the oil surface. They have about the same degree of accuracy as spirit thermometers but are much more expensive. Care should be exercised to keep them away from the coils and leads.

Resistance thermometers are very useful for determining temperatures at points inaccessible to the other types. They can be made with a higher degree of accuracy than the capillary tube type but are somewhat more expensive.

Great care is needed in placing thermometers so as to determine the temperature of the flat surfaces, such as tanks, cores, and coils. It is best to cover the bulb entirely with some material such as putty, so as to give a good surface contact and to keep the bulb from the influence of air currents on the side away from the surface. Cotton waste may be used for this purpose, but it is not quite as desirable as putty or some substance of the same nature, because it does not entirely prevent air currents from coming in contact with the bulb. For measuring temperatures between coils of air-blast transformers, a good method is to use

cork. A hole large enough to allow the thermometer bulb to be inserted should be drilled into the cork, after which it should be cut away on one side so as to leave a part of the surface of the bulb exposed, this exposed surface being set against the coil. The cork should be cut wedge-shaped with a pointed bottom, so that it will not impede the flow of the cooling medium.

Effective Temperature of Cooling Medium

As the measurement of this temperature depends to a great extent upon the method of cooling, we will take up the various methods in their order, beginning with the oil-immersed self-cooled type.

If the room temperature is kept absolutely constant throughout a heat run, its actual temperature is the effective reference base. Mercury thermometers placed in the air or in small oil cups are entirely satisfactory for the determination of this temperature. The precautions mentioned in the Standardization Rules, section 263, should be observed:

> "The thermometers indicating the room temperature should be protected from thermal radiation emitted by heated bodies, or from drafts of air, or from temporary fluctuations of temperature. Several room thermometers should be used."

As the above rule does not state that a constant room temperature is required, it may be inferred that a varying room temperature is permissible, and that the effective room temperature is the air temperature at the end of the run. Such an interpretation as this may not cause errors in the determination of rise on air-cooled apparatus but it does cause very serious errors in tests of oil-immersed transformers. The realization of this source of error has given rise to various methods of determining the effective room temperature, such as:

1. Average room temperature over several hours preceding the end of the run.
2. Final room temperature measured by thermometer in a small oil bath.
3. Average room temperature by means of oil bath for several hours preceding the end of the run.

The oil bath referred to is a small vessel filled with oil. The most commonly used is probably that standardized by the United States Navy, which consists of a steel cylinder 7.6 cm. long and 5.1 cm. in diameter, into which is drilled a hole 1.27 cm. in diameter and 3.8 cm. deep.

None of the above methods give the effective room temperature (except accidentally) because they do not take into account the fact that different transformers are affected to different degrees by varying air temperatures. Oil-immersed transformers are extremely slow in following changes in the temperature of the cooling medium. Their slowness varies directly with the size, which is a measure of thermal capacity or power of retaining heat, and inversely as their radiating ability, which is a measure of the power of dissipating heat. The thermal capacity of oil is very high, its specific heat being in the neighborhood of 0.40. The slowness of a transformer in following changes of air temperature is also noticed when it is heating up under load. The following table shows the approximate time required by several representative self-cooled, oil-immersed transformers to reach various percentages of their ultimate temperature rise when heated up on normal load.

Size of transformer	Per cent of final temperature rise		
	60	90	99
2 kv-a.	2 hr.	5 hr.	10 hr.
15 "	4 "	10 "	20 "
40 "	5 "	12 "	24 "
500 "	6 "	13 "	26 "

It will be easily seen from the above that the only accurate method of correcting for varying room temperatures is by means of some device which produces a lag behind the air temperatures corresponding in degree and in phase with the lag of the heated transformer. Since each design has its own rate of lag it is evident that a different device is needed in each case. The most satisfactory device which has been found is another transformer of the same design, preferably a duplicate of that under test. This auxiliary or idle unit should, of course, be without load and subjected to the same cooling medium as the heated transformer. Since its mass and working parts are the same as the one under test, it must of necessity be affected by varying room temperatures in exactly the same way as the heated transformer. The only difference between the two is that due to the load, so that the difference of temperature between them must be due entirely to the load.

In oil-immersed transformers, the effective temperature of the cooling medium is the average temperature of the idle unit.

This should be determined by taking the average of the top and bottom oil. If the bottom oil temperature cannot be measured directly, it may be approximated very closely by first measuring the temperature of the top oil, the top tank just under the oil level, and the bottom tank, and then calculating the average oil as follows:

If I_t is the top oil, O_t the top tank, and O_b the bottom tank temperature, the bottom oil is

$$\frac{I_t\, O_b}{O_t}$$

and the average oil temperature is

$$\tfrac{1}{2}\left(\frac{I_t\, O_b}{O_t} + I_t\right)$$

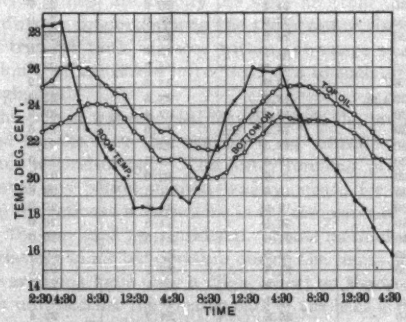


FIG. 1—IDLE TRANSFORMER RUN
185 kv-a., self-cooled, oil-immersed.

Another way in which the average temperature of the idle unit may be determined is to measure the resistance and observe the temperature before the oil is put in. Then whenever the average temperature is desired, the resistance should be measured and the temperature calculated. It is considered best, however, to use this calculated temperature merely as a check upon the temperature observed by thermometers.

Fig. 1 and Table I show the hourly readings of temperature of top and bottom oil of a 185-kv-a. idle transformer compared with room temperatures over a period of 24 hours during which the air had a total variation of approximately 10 deg. Atten-

tion is called to the corresponding cycles of the temperatures, especially to the fact that the oil cycle lags several hours behind the air in time phase and has much smaller maximum and minimum peaks than the air temperature. The bottom and top oil

TABLE I

IDLE UNIT RUN, 185-KV-A., SELF-COOLED, OIL-IMMERSED TRANSFORMER

Hour	Room temperature	Oil temperatures	
		Top	Bottom
	deg. cent.	deg. cent.	deg. cent.
2:30 p.m.	28.2	24.9	22.5
3:30	28.3	25.3	22.8
4:30	28.4	26.0	23.0
5:30	26.2	26.0	23.3
6:30	24.2	26.0	23.7
7:30	22.6	26.0	24.0
8:30	22.2	25.5	24.0
9:30	21.1	25.0	24.0
10:30	20.5	24.5	23.8
11:30	19.9	24.5	23.2
12:30 a.m.	18.3	23.5	22.5
1:30	18.4	23.4	22.2
2:30	18.2	23.0	21.5
3:30	18.3	22.5	21.0
4:30	19.4	22.5	21.0
5:30	18.9	22.0	21.0
6:30	18.6	21.8	20.6
7:30	19.4	21.6	20.0
8:30	20.5	21.5	20.0
9:30	21.6	21.5	20.0
10:30	23.5	21.8	20.3
11:30	24.3	22.7	21.1
12:30 p.m.	24.9	23.1	21.3
1:30	26.1	23.7	22.0
2:30	25.8	24.2	22.4
3:30	25.9	24.7	23.0
4:30	26.0	25.0	23.3
5:30	24.6	25.0	23.3
6:30	23.5	25.1	23.2
7:30	22.1	25.0	23.2
8:30	20.6	24.8	23.2
9:30	21.1	24.5	23.1
10:30	20.5	24.0	23.0
11:30	——	——	——
12:30	19.7	23.5	22.5

follow the same curve, the difference in temperature between them being nearly constant. The bottom oil seems to have a slight tendency to start downward later than the top oil when the room temperature is decreasing and to start upward earlier than the top oil when the room is increasing. This is probably

due to the fact that the room reaches the temperature of the bottom oil later when decreasing and earlier when increasing. The following tabulation of average values for a period of 24 hours is rather interesting.

Average	air temperature	22.45 deg.
"	top oil "	23.65 deg.
"	bottom oil temperature	22.05 deg.
"	top and bottom oil temperature	22.85 deg.

The average of the top and bottom oil is 0.4 deg. higher than the average air, but since this is within the range of accuracy of the thermometers used, no attempt will be made to explain it.

The conclusion that the idle unit and the heated transformer are affected in exactly the same way by varying air temperatures is based on the supposition that the coefficients for emission and absorption of heat are exactly the same and that the heat given out is directly proportional to the temperature rise. This is so nearly true for tank surfaces within the range of transformer operation that the errors introduced due to such an assumption are negligible.

In the case of water-cooled transformers, the problem is complicated by the fact that we have to consider two cooling mediums instead of one. The water remains practically constant over any period of time usually needed for a heat run, so that no corrections for variations in the temperature of the water during the run need be considered. Some method of correcting for variations in air temperature during the run is desirable, but these variations have only a slight effect on the temperature of the hot unit because the greater part of the heat is carried away by the water. Consequently no serious error in the temperature rise will be introduced by considering the ingoing water as the true reference base. There is, however, a small error, and it is possible that the idle unit may serve to eliminate it, or at least to give more nearly correct rises than the ingoing water temperature. We have not yet been able to obtain sufficient data on this subject to prove that the idle unit gives more nearly the effective temperature of the cooling medium than the ingoing water. In the absence of such proof, it is best to continue the past practise of using the ingoing water as the base. The errors caused by this practise will depend on the relative quantities of heat dissipated by the two cooling mediums. If all of it were taken by the water, no attention need be paid to the air temperature. However, the air does take from 10 to 30 per cent

ordinarily, so that the effective base is somewhere between the temperature of the water and that of the air.

Air-blast and air-cooled transformers follow changes in air temperature much more closely than do the oil-immersed types because their thermal capacities are considerably smaller. The ingoing air temperature may be taken as the effective base, precautions being taken to guard against sudden fluctuations. A small oil cup will serve to prevent errors due to small and sudden changes in the air and will also have a slight lag behind the air, corresponding approximately to that of the transformer.

Methods of Measuring Hot Temperatures

Hot temperatures should always be determined by resistance as well as by thermometers.

Thermometers should be placed so as to indicate the temperature of the hottest part. In oil-immersed transformers this is usually the top oil directly over the coils. In water-cooled units care must be taken to keep the thermometer away from the cooling coils, as the oil is much cooler in that vicinity, the coldest oil being between the cooling coils and the tank. In air-cooled transformers the hottest point is usually near the top of the coils and the thermometers should be placed at a number of different points on the coils so as to find this maximum.

Hot resistances may be measured by any one of the four following methods:

1. Voltmeter and ammeter.
2. Potentiometer.
3. Wheatstone bridge.
4. Kelvin or Thompson double bridge.

For such resistances a method giving quick readings is essential, as considerable error may be introduced by the cooling of windings after the load is taken off and before the resistances are measured. The quickest readings can be obtained by the voltmeter and ammeter method, for which reason its use is recommended, except for very high or very low resistances. For high resistances this method requires a very high voltage in order to produce an appreciable current, and unless the voltmeter has a high resistance itself, a large correction factor is required on account of the large part of the current taken by the voltmeter. The potentiometer or the Wheatstone bridge, although less rapid than the voltmeter and ammeter method, are better for the high resistances. For low resistances the volt-

meter and ammeter method is not desirable, because of the very large current required to produce a voltage which can be accurately measured. The Wheatstone bridge method is not accurate for such use because its resistances include leads and contacts which are a large proportion of the total resistance in such cases. The potentiometer avoids these errors and it is therefore recommended for measurement of low resistances.

In using the voltmeter and ammeter method, care must be taken to avoid including the resistance of leads and contacts. This can be done by carrying separate leads to the voltmeter and to the ammeter and attaching them at different points on the transformer leads. If the voltmeter takes an appreciable part of the total current supplied, this part should be subtracted from the measured current before the resistance is calculated. In applying the direct current an induced counter e.m.f. lowers the volt-

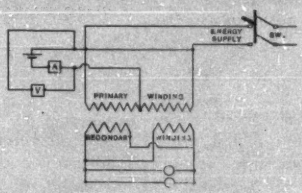


FIG. 2—APPLYING DIRECT CURRENT SO AS TO NEUTRALIZE INDUCTIVE EFFECT

meter reading for a time. This induced e.m.f. gradually disappears, but is objectionable because it delays the reading of the voltmeter. It can be caused to decrease more rapidly by raising the current at first to a value about 10 or 15 per cent in excess of that desired and then bringing it down slowly. It may be entirely eliminated in a winding provided with a middle tap or divided into two equal parts, by applying the direct current in opposite directions through the two halves as shown in Fig. 2.

In using the Wheatstone bridge the resistance of the leads from the bridge to the transformer must be subtracted from the observed value.

In determining rise by resistance by means of the voltmeter and ammeter method, the idle unit, if it is a duplicate of the heated unit, is of considerable value when used as follows: The resistance of the two units should be compared before a heat

run, care being taken to see that they are at the same temperature. The corresponding windings should be connected in series and with current forced through them the drop across each should be measured. The hot resistance of the unit under test should be compared with that of the idle unit, measurement being made in the same way as before. The rise by resistance should be calculated directly from these comparative voltmeter readings. If there is a difference between the initial resistances of the two units, a correction should be made before calculating the rise by multiplying the final resistance of the idle unit by the ratio of the initial resistances of the heated unit to the idle unit, or to put in the shape of a formula, we have

$$\text{Temp. rise} = \left(\frac{V_3 \times V_2}{V_4 \times V_1} - 1\right)(233.8 + T_1)$$

where

V_1	=	initial	resistance	voltage	of loaded	transformer
V_2	=	"	"	"	" idle	"
V_3	=	final	"	"	" loaded	"
V_4	=	"	"	"	" idle	"
T_1	=	"	temperature		" "	"

and 233.8 = the inferred absolute temperature of resistance.

This method eliminates practically all errors due to any changes in the instruments between the measurement of the cold and the hot resistance. Errors in ammeter readings can have no effect, since the same current is sent through both transformers. It is not necessary to know the actual temperature corresponding to the cold resistance because all that is needed is the comparative value when the two are at the same temperature. The final temperature of the idle unit need be known only approximately, as its temperature is the effective base and the only error caused by a mistake in reading this temperature is that due to the use of a slightly incorrect temperature coefficient.

The amount of current to be used in measuring resistance should be chosen so as not to cause any appreciable heating due to I^2R when the cold resistances are measured. This means that the direct current should not ordinarily exceed 15 to 20 per cent of the rated current of the winding.

When resistances are very low, 0.001 ohms or less, it is usually difficult to obtain accurate measurements. Consequently, it is preferable to depend upon the temperature shown by thermometer or by resistance of the other winding.

Exploring Coils

The rise by resistance shows only the average temperature of the winding. It is sometimes considered desirable to ascertain temperatures at points where it is suspected that the values will be considerably above the average. This can be done by means of small exploring coils. It is also desirable in some cases to determine the temperature of the windings without cutting off the load. This may be accomplished by means of a small exploring coil which measures a local temperature, or by means of a distributed coil which extends through a large part or all of the transformer winding.

The first form, which may be called a local exploring coil, is usually wound on some insulating material, and is thoroughly insulated from the main winding. The other form, or distributed coil, may be wound turn for turn with the transformer winding. It should be grounded to the transformer winding at one point and carefully insulated elsewhere. Either form of coil should be wound non-inductively so that the alternating current will not affect the readings or cause high induced voltages.

In general, the differences in local temperatures are not large enough to warrant the use of local exploring coils except in laboratory investigations. It is desirable to know the temperature of coils when transformers are in actual operation, but the advantage gained is not considered large enough to compensate for the added element of danger, due to the presence of exploring coils in the windings.

Cooling of Windings

Mention has been made of the cooling of the windings after load is removed. As a matter of fact, the whole transformer cools, but the rate is very slow in the case of oil-immersed types. The thermal capacity of the coils, however, is much less than that of the other parts and as a result, the windings cool to the average temperature much more quickly than the entire transformer cools to the air or cooling medium. For instance, the thermal capacity of the copper of a certain 185-kv-a. transformer is about 98,000 joules, while that of the oil is about 2,200,000 joules. The rate of this cooling of windings may be calculated as follows:

The windings are at a constant temperature rise above oil before the load is taken off, so that the rate at which they are giving out heat is the same as the rate at which energy is being put into them, or in other words, it is the copper loss. This rate

continues for a short period after the load is taken off. The thermal capacity of a pound of copper is about 177 joules. Then, if the coils are giving out heat at the rate of one watt per pound (0.45 kg.), one joule will be lost during the first second after shut-down. This will cool the coil 1/177th of a degree in the first second, and 60 times this amount, 0.342 deg., in the first minute. At three watts per pound (0.45 kg.) the cooling in the first minute would be approximately 1.04 deg. These values will be modified to some extent by the fact that the insulation of the coil has a certain thermal capacity, thus increasing the total value and decreasing the rate of cooling. This rate decreases as the coil comes nearer and nearer to the oil temperature, reaching the zero value when the rise above oil becomes zero. The curve of

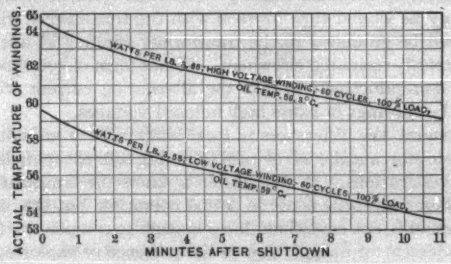


FIG. 3—COOLING CURVES OF WINDINGS
100-kv-a., self-cooled, oil-immersed transformer.

temperature against time is logarithmic in shape, the rate of cooling at any point being proportional to the rise above the base temperature. The total time of cooling varies with the design, but in ordinary cases it is between 30 and 60 minutes. We are interested mostly in the first minute or two, and during this period there is very little change in the rate. If the watts loss per pound of copper is known, an approximate correction can be made by calculating the initial rate, noting the time at which the resistance reading is obtained and multiplying this time by the rate, finally adding this to the measured temperature rise. This correction is, however, only approximate and should not be applied for periods of more than a few minutes. Another method which gives more accurate results is to take readings of resistance over a period of six or eight minutes so as to determine the shape of

the cooling curve, then prolong the curve so as to show the initial resistance. This method has the disadvantage that it allows the transformer to cool considerably and thus prolongs the heat run in case any further measurements are desired, such as the rise by resistance of the other winding.

Representative cooling curves of windings of self-cooled oil-immersed transformers are shown in Figs. 3 and 4.

The rate of cooling of windings in air-blast transformers is lessened considerably if the air is shut off simultaneously with the load. In fact it is quite often found that the thermometers on the coils indicate an increase in temperature for the first few minutes. This is probably because the shutting off of the air supply leads to an equalization of temperature throughout the coils, thus reducing the higher and increasing the lower temperatures.

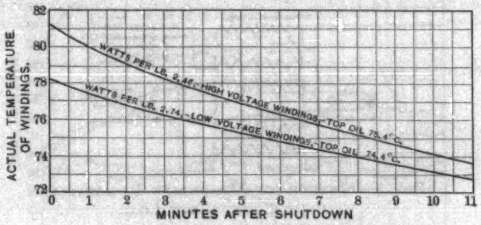


FIG. 4—COOLING CURVES OF WINDINGS
100-kv-a., self-cooled, oil-immersed transformer.

MEASURING RESISTANCE WITHOUT CUTTING OFF LOAD

Resistance of windings having a middle tap or divided in two equal parts may be measured while the load current is passing through them, by the method shown in Fig. 5. This figure shows the ordinary connections for a bucking run on two transformers, each of which is provided with a middle tap in each winding. The excitation or core loss voltage is applied to the two high-voltage windings connected in multiple, while the copper loss is supplied in series with the two low-voltage windings. When it is desired to measure the resistance of the high-voltage windings in this case the direct current is applied to the middle points of the two windings, between which there is no difference of potential due to the alternating current. The direct current flows in opposite directions in the two halves, thus neutralizing its own inductive

effect. The measured resistance is that of the two windings in multiple. It will be noted that this measurement can be made without disturbing the heat run connections or losses in any way.

It is usually considered desirable, however, on account of safety, to cut off the excitation or core loss supply while the direct-current instruments are being read.

The middle points of the low-voltage windings shown in the figure are not at the same potential, because of the unbalancing due to the copper loss supply voltage which is in series with them. This makes it necessary to provide an auxiliary or equalizing coil so as to provide an artificial middle point. This equalizing coil may be one of the windings of a similar transformer. The measured resistance is that of the two halves of the equalizing coil connected in multiple with the two halves of the loaded trans-

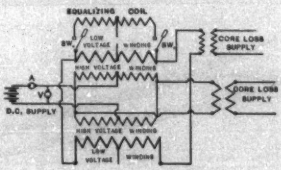


FIG. 5—METHOD OF MEASURING RESISTANCE WITHOUT CUTTING OFF LOAD

former. The actual value of the resistance of the transformer may be calculated after the resistance of the equalizing coil alone has been measured.

This method is too complicated for general use, but is desirable where it is not convenient to cut off the load for resistance measurements and where a large error would be caused by cooling of windings. It has several advantages over the old method, among which the following may be mentioned:

1. It makes it possible to measure resistance as often as desired without lengthening the heat run.

2. It eliminates drop in temperature due to cutting off load while measuring resistance.

HEAT RUN WITH IDLE UNIT

Fig. 6 and Table II give a record of a heat run on a 500-kv-a. oil-immersed self-cooled transformer; temperatures of top oil

of idle unit, top oil of heated unit and of surrounding air being shown each hour during a period of about four days. The comparative rises of the heated unit above air and above the top oil of the idle unit have also been plotted. Particular attention is called to the wide variation in room temperature as compared with the top oil temperature of the two transformers. Each of the three curves shows cycles corresponding to 24-hour periods. The oil temperature cycles lag several hours behind the air, those of the idle unit being practically in phase with those of the hot unit. The cycles of rise above air are the reverse of those of air temperature and have about the same range of temperature. The rise above the top oil of idle unit also shows, faintly, cycles in phase with those of the rise above air, but the variations in the

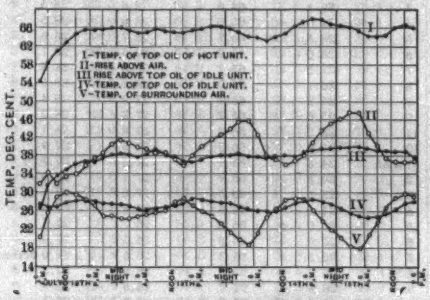


FIG. 6—HEAT RUN ON TRANSFORMERS
500-kv-a., oil-immersed, self-cooled.

value of this rise are considerably less than those of the rise above air. The fact that these cycles are in phase with the rise above room indicates that the idle unit does not entirely compensate for variations in air temperatures, or, in other words, that it is not affected to as great an extent as the heated unit by such variations. This may be true, but even if it is, the test shows that the idle unit gives far more consistent results than any other method so far suggested. The approximately correct temperature rise may be determined by calculating the rise above room each hour for a complete cycle of 24 hours after ultimate rise is reached, and averaging the result. This method, although too expensive for general use, is useful in some cases and gives some interesting data in this case.

TABLE II
NORMAL LOAD HEAT RUN ON 500-KV-A. SELF-COOLED OIL IMMERSED TRANSFORMER.

Day	Hour	Room temperature	Top oil temperatures		
			Loaded transformer	Permanently screened idle transformer	Alternately screened idle transformer
		deg. cent.	deg. cent.	deg. cent.	deg. cent.
July 12	7 a.m.	20.5	54.5	27.5	27 Screened
"	8	23.0	57.5	27.0	26.6
"	9	25.7	58.5	27.0	26.6
"	10	27.5	59.5	27.1	26.9
"	11	29.0	61.0	27.2	27
"	12	29.5	63.0	27.8	27.6
"	1 p.m.	30.0	63.2	28.1	28.0
"	2	30.0	64.0	28.2	28.0
"	3	29.5	64.8	28.6	28.5
"	4	29.0	65.0	28.6	28.5
"	5	28.5	65.7	28.7	28.6
"	6	28.0	65.6	28.5	28.7
"	7	27.5	65.7	28.3	28.8
"	8	26.7	65.7	28.1	28.5
"	9	25.3	65.7	27.9	28.4
"	10	25.0	65.7	27.7	28.2
"	11	25.0	66.0	27.6	28.1
"	12	25.0	66.3	27.5	27.9
July 13	1 a.m.	24.5	66.1	27.3	27.7
"	2	24.5	65.7	27.1	27.6
"	3	23.5	65.5	27.0	27.4
"	4	24.5	64.8	26.8	27.3
"	5	25.0	65.0	26.7	27.3
"	6	25.5	65.2	26.5	27.0
"	7	25.5	65.3	26.6	27.0 Screen removed
"	8	26.0	65.8	26.6	27.3
"	9	26.8	65.9	26.5	28.0
"	10	26.5	66.0	26.6	28.5
"	11	26.5	65.5	27.0	28.9
"	12	27.5	64.9	27.0	29.1
"	1 p.m.	28.0	65.2	27.5	29.8
"	2	28.5	65.2	28.0	29.9
"	3	29.0	65.3	28.4	30.5
"	4	28.5	65.7	28.5	30.8
"	5	27.5	65.7	28.9	31.0
"	6	27.0	66.0	28.7	30.9
"	7	26.0	66.2	28.7	30.9
"	8	25.5	66.4	28.7	30.7
"	9	25.0	66.6	28.4	30.6
"	10	24.0	66.7	29.6	30.3
"	11	23.7	66.4	28.1	30.0
"	12	23	66.3	27.8	30.0
July 14	1 a.m.	21.8	65.8	27.5	29.5
"	2	21.0	65.5	27.2	29.2
"	3	20.0	65.5	27.0	28.8
"	4	19.5	65.0	26.5	28.5
"	5	19.0	64.4	26.4	28.0
"	6	20.0	64.3	26.2	27.8
"	7	21.5	64.1	26.0	27.8
"	8	23.0	63.2	25.9	27.7 Screened

TABLE II—*Continued.*
NORMAL LOAD HEAT RUN ON 500-KV-A. SELF-COOLED OIL-IMMERSED TRANSFORMER

Day	Hour	Room temperature	Top oil temperatures		
			Loaded transformer	Permanently screened idle transformer	Alternately screened idle transformer
		deg. cent.	deg. cent.	deg. cent.	deg. cent.
July 14	9 a.m.	25.0	63.5	25.9	27.5
"	10	25.5	64.0	26.0	27.6
"	11	27.0	64.5	26.3	27.8
"	12	28.0	64.4	26.6	28.1
"	1 p.m.	29.0	65.3	27.0	28.4
"	2	29.0	65.8	27.2	28.8
"	3	29.0	66.2	27.8	29.3
"	4	29.0	66.9	28.0	29.4
"	5	29.0	67.4	28.8	30.0
"	6	28.0	67.7	28.5	29.7
"	7	26.5	67.9	28.5	29.7
"	8	26.0	68.0	28.5	29.5
"	9	24.0	67.8	28.0	29.0
"	10	22.5	67.6	27.8	28.7
"	11	22.0	67.4	27.5	28.3
"	12	21.0	67.0	27.0	27.8
July 15	1 a.m.	20.5	66.7	26.7	27.5
"	2	19.0	67.0	26.0	27.0
"	3	18.5	66.2	25.7	26.8
"	4	18.5	66.0	25.5	26.2
"	5	18.0	65.5	25.0	26.0
"	6	20.0	64.8	24.7	25.5
"	7	21.4	64.5	24.8	25.4
"	8	23.2	64.5	24.8	25.8 Screen removed
"	9	24.2	64.5	24.8	26.0
"	10	25.7	64.5	25.0	26.4
"	11	27.2	64.7	25.4	27.0
"	12	27.7	65.0	26.1	27.8
"	1 p.m.	29.1	66.0	26.8	28.3
"	2	29.2	66.3	27.0	29.0
"	3	30.0	66.8	27.7	29.4
"	4	29.5	66.9	28.1	29.8
"	5	29.3	66.2	28.3	30.2

The following table shows the average value of the five curves in Fig. 6 for two periods of 24 hours each:

Average temperature for 24-hour periods:

1st day. From 13th at 2:00 P.M. to 14th at 1:00 P.M., incl.
2nd " " 14th " 2:00 " " 15th " 1:00 " "

	1st day	2nd day
Average air temperature	24.45 deg. cent.	24.10 deg. cent.
" top oil of idle unit	27.35 " "	26.60 " "
" " " " hot unit	65.25 " "	66.15 " "
" rise above air	40.75 " "	42.0 " "
" " " idle unit	37.85 " "	39.4 " "

	1st day	2nd day
Max. variation of air from average.....	+4.45 to —5.45	+4.9 to —6.1
" " " idle from average.....	+1.55 to —1.55	+1.9 to —1.9
" " " hot unit from average....	+1.45 to —2.05	+1.85 to —1.75
" " " rise above idle unit from average.....	+0.65 to —0.95	+1.0 to —1.0
Rise above air from average.....	+3.80 to —4.45	+5.7 to —5.2

Assuming that the average rise above air is the correct value, which is probably true, it is evident that the rise above top oil of idle unit is in this case between two and three degrees too low. This shows the importance of using the average instead of the top oil as the base temperature. Later tests, one of which is plotted in Fig. 1, show that the average of top and bottom oil for a period of 24 hours is the same as the average air. These tests also show that the top and bottom oil follow the same curve. So the rise above average oil, if it had been measured and plotted in Fig. 6, would undoubtedly follow the curve of rise above top oil, except that all values would be from two to three degrees higher.

Method of Using Idle Unit

The idle unit should be subjected to exactly the same cooling conditions as the heated unit. Care should be taken to place it far enough away so as to prevent its temperature being raised due to the heat radiated from the hot unit. This distance depends upon the size of the unit and the amount of heat radiated. In some cases it is desirable to place a heavy screen between the two units.

Fig. 7, plotted from Table II, shows the effect of screening upon an idle unit placed about 90 cm. away from the heated 500-kv-a. transformer. The hot and the idle units were duplicates, each being placed in a corrugated sheet steel tank of oval shape having floor space of 145 by 89 cm. and a height of 245 cm. They were placed with the long sides next each other. The temperature rise of the oil in the heated unit was in the neighborhood of 40 deg. above the idle unit. It will be noted that the idle unit when unscreened shows a temperature rise of top oil approximately 1.5 deg. higher than when screened. The effect of the hot unit upon the idle unit can be calculated roughly as follows:

The percentage of heat radiated by the hot unit in a corrugated tank is about 25 per cent of the total, the remainder being carried away by convection. This radiated heat is given off in straight lines in every direction. If we should surround the hot unit by means of a screen 90 cm. distant at all points, it would intercept all of the radiant heat. The idle unit does intercept a

certain percentage of this heat, which percentage can be calculated by finding the ratio of the area of the idle unit to that of a complete envelope around the hot unit. In the case of the 500-kv-a. unit shown in Fig. 7, this ratio is about 0.15. This means that the idle unit receives 15 per cent of 25 per cent of the total heat dissipated by the hot unit, or 3.75 per cent. The temperature rise of the idle unit will be 3.75 per cent of that of the hot unit, which amounts to about 1.4 deg. in this case.

This test is also of interest with reference to the spacing of loaded transformers under test or in operation. If two loaded units, instead of one idle and one loaded, had been used, it is evident that since the two would be at the same temperature, neither could give heat to the other, and that the effective radiation from each would be decreased by the amount of heat given to the unscreened idle unit in the test. This would result

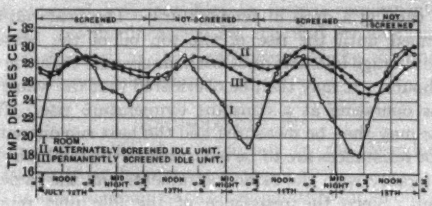


FIG. 7—EFFECT OF SCREENING IDLE UNIT

in a higher temperature rise, amounting to about 1.4 deg. cent. in each transformer.

The temperature of the idle unit may be determined in several ways. If the variations in air temperature are not large, or if the height of the idle unit is small, the top oil temperature will be sufficiently accurate. However, it is preferable to use the average of top and bottom oil temperature, the bottom oil temperature being measured directly when possible. If this is not possible the temperature may be calculated by means of the following formula:

$$\text{Average temperature of idle unit} = \frac{1}{2}\left(\frac{I_t O_b}{O_t} + I_t\right)$$

when

I_t is the top oil temperature
O_t is the top tank temperature at oil level
O_b is the bottom tank temperature.

The cold resistance of the idle unit should be carefully compared with that of the unit to be heated up, especial care being taken to have the two at the same temperature or to know the exact temperature of each. This comparison may be made before the oil is placed in the transformer, and it is best to make the comparison at this time if the oil temperature differs greatly from that of the room, because considerable time will be lost in determining the average temperature of the windings in each unit after they are filled with oil. This comparison of resistances should preferably be made by forcing current through corresponding windings connected in series and reading the drop across each. Several readings should be taken in order to make sure that the exact ratio of the cold resistances has been determined.

The heat run may be started as soon as desired after the above ratio has been measured. It is best not to take readings of resistance until the end of the run, since the load must be taken off, thus causing a drop in temperature. The heat run should be continued until the rise of the top oil of the heated unit above the average idle unit does not change more than one degree in three hours. It may then be considered that the whole transformer is operating at a constant temperature rise. The hot resistance may then be measured and the heat run discontinued.

The hot resistances are to be measured in the same way as the cold, preferably with the same instruments and the same value of current. Since the resistance of the idle unit represents the true effective temperature of the cooling medium, the rise by resistance may be calculated by means of the formula

$$\text{Temp. rise} = \left(\frac{V_3 \times V_2}{V_4 \times V_1} - 1\right)(233.8 + T_1)$$

where

$V_1 =$ initial resistance voltage of loaded transformer
$V_2 =$ " " " " idle "
$V_3 =$ final " " " loaded "
$V_4 =$ " " " " idle "
$T_1 =$ final temperature of idle transformer
and 233.8 = the inferred absolute temperature of resistance.

Although the voltmeter and ammeter method is the only one referred to in the above discussion, it is to be noted that the other methods can be used in the same manner with good results, especially where the galvanometer is so constructed as to give quick readings. A potentiometer may be substituted for the

voltmeter when a low voltage is to be measured. The bridge methods are well adapted for this use, as the two resistance ratios can be measured directly by connecting the idle unit as the known and the loaded unit as the unknown resistance in the bridge circuit.

The advantages of the idle unit for determination of rise by resistance are not restricted to the oil-immersed self-cooled type of transformer. It is equally good for other types, regardless of the method of cooling. A slight modification of the method is required in the case of water-cooled oil-immersed transformers if it is desired to use the ingoing water temperature as the base, that is, the rise should be calculated as specified above and then the difference in temperature between the average oil of the idle unit and the ingoing water should be added to the calculated rise. As stated before, we know that the ingoing water temperature is not the effective temperature of the cooling medium unless the air and water are at the same temperature. However, we have not yet obtained sufficient data to justify recommending any other base. No modifications are required for air-blast or air-cooled transformers, as the temperature of the windings is the effective reference temperature.

Recommendations

It is recommended that additions to the Standardization Rules be made as follows:

(1) The effective room or base temperature for an oil-immersed transformer is the temperature of an idle unit similar to and prepared for test the same as that run in test, and its temperature is the average of the top and bottom oil, the bottom oil temperature being measured directly by a thermometer or calculated by multiplying the bottom tank temperature by the ratio of the top oil to the top tank temperature.

(2) When a duplicate transformer is available, the rise by resistance should be determined by first comparing the resistance of the two when at the same temperature, subjecting the idle transformer to the same cooling conditions as the loaded one until hot resistances are to be measured, then comparing the resistances of the two in the same manner as before, and calculating the rise from these final readings, correcting for any difference in the two initial resistances by multiplying the final resistance of the idle unit by the ratio of initial resistance of the loaded unit to the idle unit.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

METHODS OF DETERMINING TEMPERATURE OF TRANSFORMERS

BY W. M. McCONAHEY AND C. FORTESCUE

I. Introduction

Temperature, in most electrical apparatus, plays an important part in the question of satisfactory operation. It affects not only the working efficiency but also the life of the apparatus, since the fibrous materials of which the greater part of the insulation is composed soon deteriorate under high temperatures. There is perhaps no other factor of such importance to satisfactory operation which is so difficult to measure accurately, and also is influenced to such an extent by external conditions, as the temperature of electrical apparatus under load.

This paper will give a brief discussion of conditions that affect the operating temperature of transformers and the relative merits of different methods of measuring temperatures. A description will be given of the various methods of loading, and a comparison will be made between temperatures obtained by a new method of loading a single transformer with those obtained by the standard method of loading which requires two transformers.

II. Conditions Affecting the Temperature of Transformers

In air-cooled transformers such as those designed to operate by natural ventilation without oil the temperature is directly dependent upon that of the air in the room. Thermometers, to measure correctly the air temperature in a room, should be placed well in the open. As a general rule, about the height to be comfortably read will be right. Small apparatus may be affected in temperature by the cool stream of air near the floor of the room

and it will therefore be advisable in such cases to have thermometers placed about half the height of the apparatus from the floor, in which position they will give about the proper temperature of the air that comes in contact with the transformers.

Variation in room temperature has but little effect on the temperature rise of transformers which depend on direct cooling by air, but where the air serves to cool some medium of high specific heat which in turn serves as the true cooling medium, fluctuation in the air temperature will produce apparent rises in temperature that are far from correct. The best of care should be taken to have the temperature of the air in the room in which such apparatus is tested, as uniform as possible. It has been suggested that a similar transformer to that on test be placed in the room and the temperature rise of the transformer on test be based on the temperature of the idle transformer. This is an admirable way of overcoming the effect of fluctuation in air temperature and will give correct results, but it is open to the objection that an additional transformer is required.

Air-cooled and oil-insulated air-cooled transformers depend for cooling chiefly on convection currents of air and it is important, therefore, that they shall have a free circulation of air from every point and that there be enough head-room to carry off the heated air.

The coils and iron in an oil-insulated transformer depend upon convection of the oil for their cooling. Ventilating ducts must therefore be well distributed among the coils in such a way that as little as possible of the winding is blanketed. The larger the transformer the more important this becomes. The rate of flow of the oil will depend upon the area of the ducts, their length, the watts per unit area of exposed surface and the viscosity of the oil. An excellent test to determine the freedom of flow of the oil is to measure the difference of temperature between the bottom and top oil, as it enters and leaves a duct. In oil-insulated air-cooled transformers, however, a large difference between top and bottom oil does not necessarily mean constricted ducts. It may be due to poor design of the cooling case, whereby the air convection currents meet with resistance, and this in turn reacts on the flow of the oil, since the source of the head of both oil and air currents is the difference in temperature between the top and bottom of the coils themselves.

The different parts of the apparatus should be ventilated according to their individual requirements. Certain limitations due

to structure prevent full advantage being taken of the characteristics of different materials in a transformer. Thus, iron loss decreases as the temperature of the iron is increased, but it is impossible to take advantage of this property of iron to any great extent. Moreover, the coils are so intimately associated with the magnetic circuit that it would ordinarily be a difficult matter to maintain them at widely differing temperatures. In oil transformers the temperature of the external surface of any part of the apparatus must necessarily be limited to a temperature less than that at which oil becomes injuriously affected, since there is always a film of oil at the surface which is held there by surface tension and moves only very sluggishly.

III. Tests for Efficiency of Cooling

The places in a transformer at which the temperature is likely to be a maximum depend largely upon the type and construction. In modern, section-wound, shell and core type transformers the ventilation should be so carefully designed that there can be no hot spots, so that the difference between the maximum and average temperature of the coils will practically be the same as the difference between the average temperature of the oil and that of the top or hot oil. Thus, if the maximum temperature of the oil in the ducts is 10 deg. higher than its average temperature, the maximum temperature of the coils will also be about 10 deg. higher than their average temperature.

In order to obtain a proper conception of the efficiency of the ventilation of a transformer it is necessary to know not only the temperature of the top oil but also that of the oil as it enters the ducts, because the average temperature of the transformer winding depends upon the average temperature of the oil and the maximum temperature of the winding depends upon the maximum temperature of the oil. There may be a large difference between the maximum and average values and it is quite possible to have a transformer which seemingly runs cool but the insulation of which will in time deteriorate on account of the high maximum temperature of the winding. In wire-wound coils great care has to be exercised in the design in order to avoid large differences in temperature between the inner and outer conductors. There is no very good method of measurement which will enable one to find the temperature gradient through the coil.

The following rule may be used to estimate its approximate

value when the average temperature of the coils and oil are known:

θ_1 = Estimated value of temperature gradient through external insulation of coil.

θ_2 = Average temperature of coil above average oil.

θ = Temperature gradient through coil.

$\theta = 1\frac{1}{2}\,\theta_2 - \frac{1}{2}\,\theta_1$

θ_{max} = Maximum temperature rise of oil + θ.

This formula assumes, as a matter of course, that the coils are efficiently ventilated.

Thermometers in a transformer can be used only to indicate temperatures in the coils, not to measure them. Their usefulness consists in their ability to show up anything abnormal, such as the constriction of a duct. In other words, if a thermometer indicates a winding temperature differing very much from that of the hot oil, it is an indication that there is something wrong with the ventilation at that point. It has been proposed that thermocouples be used to determine the maximum temperature of transformer coils under load. It is impossible to tell the exact location of the hottest place in a coil and it would therefore be necessary, if such a method were adopted, to place a number of couples at all the places likely to have a high temperature. It is very difficult to see how such a scheme could be used without danger both to the operator and the apparatus. The only suitable place for the application of such methods is in the laboratory where proper precautions can be taken and where the work is done by skilled operators.

The average temperature can be obtained by the resistance method. The work of measuring the resistances of the windings of an oil transformer should be done as quickly as possible because the coils, on account of their small specific heat, quickly lose their temperature above the oil. Probably the best way for measuring high resistances is by means of the Wheatstone bridge, while for low resistances the Kelvin bridge may be used. Whatever method is used, the settings of the instruments should be adjusted for the approximate values so that the time required for the final adjustment may be reduced to a minimum.

The authors are of the opinion that for commercial testing the thermometer and resistance methods of measuring temperatures should be adhered to, as by their means and with the exercise of care in making the tests the efficiency of cooling of a transformer may easily be determined.

IV. Methods of Loading Transformers for Temperature Test

Transformers may be loaded directly on resistance racks or any other means for dissipating power; or two or more of them in combination may be artificially loaded. The first method of loading, on account of the expense involved, is limited to small transformers and special transformers where there is only one on order. The second method is economical in application, flexible in operation and is by far the most satisfactory.

The methods hitherto in use for artificially loading transform-

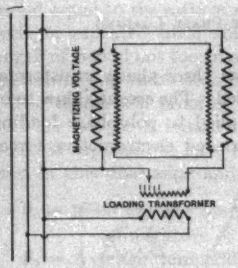


Fig. 1—Loading Scheme for Two Transformers

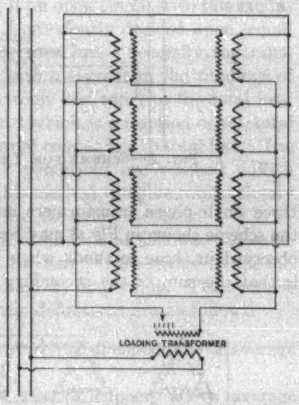


Fig. 2—Loading Scheme for More than Two Transformers

ers are applicable only when more than one transformer is available. They are all modifications of one scheme, which is that used for loading two single-phase transformers and is commonly referred to as the "opposition method," shown in Fig. 1. Excitation voltage may be supplied from the same circuit as the load current or it may be taken from an independent circuit of the proper frequency for the transformer. Where a large number of similar transformers are to be loaded at the same time their primary windings may be connected in parallel and their secondaries may also be connected in parallel, or the secondary of one

transformer in a group may be paired with that of one of the opposition group independently of the secondaries of the other transformers in the same group. (See Fig. 2). When there are

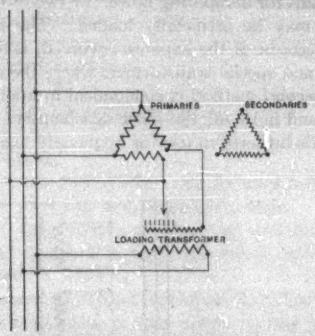


FIG. 3—SCHEME FOR THREE-PHASE LOADING

three single-phase transformers or one three-phase transformer the scheme shown in Fig. 3 may be used. The essential law to be observed in these methods when applied to polyphase loading is that the sum of the secondary induced electromotive forces

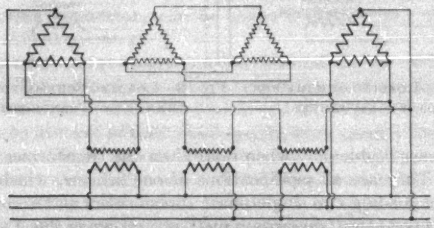


FIG. 4—SCHEME FOR THREE-PHASE BALANCED LOADING

taken around the circuit shall be zero. Six single-phase transformers or two three-phase transformers may be made to take a balanced load from a three-phase circuit by the scheme shown in Fig. 4.

V. Alternate Open-Circuit and Short-Circuit Method

The methods of loading transformers just described are applicable only when there are two or more transformers to be tested. It is sometimes necessary to test a single transformer, and it is generally impossible to obtain another suitable one to run in opposition. The following method has been devised to meet this condition.

The alternate open-circuit and short-circuit method of loading a transformer is effected by first exciting the transformer to be tested so as to obtain a core loss equal in value to the total losses of the transformer and running it on open circuit with this excitation for a fraction of a period t, previously decided upon, equal to the ratio of normal iron loss to total loss. Secondly, the transformer is run on short circuit with a current in the windings of such value as to give a short-circuit loss equal to the total loss, for the remainder of the period t which is a fraction of the total period equal to the ratio of normal copper loss to total loss. The cycle is repeated until steady conditions are reached. With length of period not too great this method will give results closely approximating those obtained by the other methods.

The theoretical proof of this method is as follows: Assume that the copper is initially at the same temperature as the oil, which is supposed to have reached its final value. The symbols used in this discussion and their definitions are as follows:

θ_c = Final average temperature rise of copper above average temperature of oil.

θ_1 = Average temperature rise of copper above average temperature of oil at end of first cycle.

θ_2 = Average temperature rise of copper above average temperature of oil at end of open-circuit run in second cycle.

θ_3 = Average temperature rise of copper above average temperature of oil at end of second cycle.

$\theta_{(2n-1)}$ = Average temperature rise of copper above average temperature of oil at end of nth cycle.

θ_{2n} = Average temperature rise of copper above oil at end of open-circuit part of $(n+1)$th cycle.

α = Emissivity of coil surface exposed to oil, in watts per sq. in. per deg.

S_c = Total surface of coil exposed to oil, in sq. in.

W = Weight of copper, in lb.

x = Time measured from start of run, in hours.
t = Period in hours.
E_c = Normal copper loss.
E_1 = Normal iron loss.
θ_a = Temperature at end of time x_1 on short-circuit.
θ_b = Temperature at end of time x_2 on open-circuit.

The value of the average rise in temperature of the coils above the average temperature of the coil is given by

$$\theta_c = \frac{E_c}{\alpha S_c} \tag{1}$$

With a copper loss E and measuring the time x from the instant at which the average temperature of the oil and coils are the same, the temperature rise of the coils above the oil will be

$$\theta = \frac{E}{\alpha S_c}\left(1 - \frac{1}{10^{\frac{8.75\,\alpha\, S_c\, x}{W}}}\right) \tag{2}$$

At the end of time x_1 we shall have

$$\theta_a = \frac{E\,\theta_c}{E_c}\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,x_1}{W\,\theta_c}}}\right) \tag{3}$$

If at the end of this time x_1 the load be removed and the transformer run on open circuit the copper will cool and its temperature at the end of time x_2 will be

$$\theta_b = \frac{\theta_a}{10^{\frac{8.75\,E_c\,x_2}{W\,\theta_c}}} \tag{4}$$

Considering a cycle of period t, the length of the short-circuit portion of the period is

$$\frac{E_c}{E_c + E_f}\,t$$

The temperature rise of the coils above the average oil at the end of this time will then be

$$\theta_1 = \frac{(E_c + E_f)\,\theta_c}{E_c}\left(1 - \frac{1}{10^{\frac{8.75\,E_c^2\,t}{W\,(E_c+E_f)\,\theta_c}}}\right)$$

or, designating $\frac{(E_c + E_f)\,\theta_c}{E_c}$ by θ_T,

$$\theta_1 = \theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)$$

Similarly,

$$\theta_2 = \frac{\theta_1}{10^{\frac{8.75\,E_f\,t}{W\,\theta_T}}}$$

$$\theta_3 = \theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right) + \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{10^{\frac{8.75\,(E_f + E_c)\,t}{W\,\theta_T}}}$$

$$\theta_4 = \frac{\theta_3}{10^{\frac{8.75\,E_f\,t}{W\,\theta_T}}}$$

$$\theta_5 = \theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)$$

$$+ \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{10^{\frac{8.75\,(E_f + E_c)\,t}{W\,\theta_T}}} + \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{10^{\frac{8.75 \times 2\,(E_f + E_c)\,t}{W\,\theta_T}}}$$

$$\theta_{(2n-1)} = \theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right) + \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{10^{\frac{8.75\,(E_f + E_c)\,t}{W\,\theta_T}}} + \cdots$$

$$+ \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{10^{\frac{8.75\,(n-1)\,(E_f + E_c)\,t}{W\,\theta_T}}} \tag{5}$$

$$\theta_{2n} = \frac{\theta_{(2n-1)}}{10^{\frac{8.75\,E_f\,t}{W\,\theta_T}}} \tag{6}$$

The expansion for θ_{2n-1} is a geometrical progression which is convergent, hence we have

$$\theta_{(2\infty-1)} = \frac{\theta_T\left(1 - \frac{1}{10^{\frac{8.75\,E_c\,t}{W\,\theta_T}}}\right)}{1 - \frac{1}{10^{\frac{8.75(E_c+E_f)t}{W\,\theta_T}}}} \tag{7}$$

$$\theta_{2\infty} = \frac{\theta_{(2\infty-1}}{10^{\frac{8.75\,E_f\,t}{W\,\theta_T}}} \tag{8}$$

If the length of the period t be made exceedingly small,

$$\theta_{2\infty-1} = \theta_{2\infty} = \theta_T \frac{E_c}{E_c + E_f} = \theta_c \tag{9}$$

Hence, for very small periods the final value is the same as that obtained under normal load conditions. It remains to be seen how much of an error is caused by the length of the period t being finite.

Let us apply this to an actual case of a 150-kv-a. transformer. In this transformer

$$E_f = 1390 \text{ watts}$$
$$E_c = 1136 \text{ watts}$$
$$(E_f + E_c) = 2526 \text{ watts}$$
$$\theta_c = 17 \text{ deg.}$$
$$\theta_T = 37.8 \text{ deg.}$$
$$W = 270 \text{ lb.}$$
$$t = \tfrac{1}{2} \text{ hr.}$$

$$\frac{8.75\, E_f\, t}{W\, \theta_T} = 0.596 \qquad 10^{\frac{8.75\, E_f\, t}{W\, \theta_T}} = 3.945$$

$$\frac{8.75\, E_c\, t}{W\, \theta_T} = 0.486 \qquad 10^{\frac{8.75\, E_c\, t}{W\, \theta_T}} = 3.062$$

$$\frac{8.75\, (E_c + E_f)\, t}{W\, \theta_T} = 1.082 \qquad 10^{\frac{8.75\, (E_c + E_f)\, t}{W\, \theta_T}} = 12.08$$

$$\theta_{(2\infty - 1)} = 28.5 \text{ deg.}$$
$$\theta_{2\infty} = 7.2 \text{ deg.}$$

The average of these two is 17.85 deg., which is close enough to the correct value $\theta_c = 17$ deg.

For a period $t = \tfrac{1}{4}$ hr.

$$\theta_{(2\infty - 1)} = 23.3 \text{ deg.}$$
$$\theta_{2\infty} = 11.74 \text{ deg.}$$
$$\text{Average} = 17.52 \text{ deg.}$$
$$\theta_c = 17.00 \text{ deg.}$$

Evidently in this particular case there is very little to be gained in accuracy by making the period t less than one-half hour. In transformers which have high copper loss as compared with iron loss it may be found necessary to use a period of less than one-half hour.

VI—Temperature Tests on Transformers by the Alternate Open-Circuit and Short-Circuit Method

Tests were made on a 150-kv-a. 60-cycle oil-insulated air-cooled transformer to obtain a comparison between this method and the standard opposition method. The results of the various tests made indicate a good check between the two methods. The transformers chosen agreed closely in characteristics, but in order

to eliminate any error due to possible differences between them, they were interchanged in the second run. The following are the principal values taken from the test results for the purpose of comparison. The thermometer readings were taken at the middle of the short-circuit part of the cycle. The temperature rises by resistances are a mean between those obtained at the beginning and end of the short-circuit part of the cycle.

TEMPERATURE RISES AT FULL LOAD AFTER STEADY CONDITIONS WERE REACHED

	Opposition method	Alternate short-circuit and open-circuit method
Temperature rise of low-tension coils by thermometer	38.5	37
Temperature rise of high-tension coils by thermometer	33.5	35
Temperature rise of top oil	31.5	32
Temperature rise of bottom oil	10.5	11

RISE OF TEMPERATURE OF WINDING BY RESISTANCE

	Opposition method	Alternate short-circut and open-circuit method
High-tension	33.9	34.6
Low-tension	40.7	41.5

These results are seen to be in very close agreement. The readings obtained on a second run with the two transformers interchanged are as follows:

TEMPERATURE RISES AT FULL LOAD AFTER STEADY CONDITIONS WERE REACHED

	Opposition method	Alternate open-circuit and short-circuit method
Temperature rise of low-tension coils by thermometer	35	36
Temperature rise of high-tension coils by thermometer	34	32
Temperature rise of top oil	29	30
Temperature rise of bottom oil	9	10

TEMPERATURE RISE MEASURED BY INCREASE OF RESISTANCE.

	Opposition method	Alternate open-circuit and short-circuit method
High-tension	33	34.4
Low-tension	39	41.0

All the results cited above were taken with a 30-minute period. The following rises by resistance were taken with a 15-minute period.

TEMPERATURE RISE MEASURED BY INCREASE OF RESISTANCE.

	Opposition method	Alternate open-circuit and short-circuit method
High-tension	33	33.3
Low-tension	39	39.6

A third test at 125 per cent load was made on the same transformers for temperature rises by the resistance method, with the following results.

TEMPERATURE RISE AT 125 PER CENT LOAD, MEASURED BY INCREASE OF RESISTANCE METHOD

	Opposition method	Alternate open-circuit and short-circuit method
High-tension	43	42.6
Low-tension	53	53.3

This method was also tried on a 2500-kv-a. water-cooled transformer, in comparison with the opposition method, the same flow of water being used in each case. The length of period was 15 minutes. The results were:

TEMPERATURE RISE ABOVE COLD WATER

	Opposition method	Alternate open-circuit and short-circuit method
High-tension	41.1	41.1
Low-tension	39.5	39.4

The tests were run a second time with the same results.

The results given indicate that the method of alternate short-circuit and open-circuit, as carried out, gives a very close approximation to the conditions of temperature obtained under load.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

CORRECTION OF TRANSFORMER TEMPERATURES FOR VARIATION IN ROOM TEMPERATURE, TAKING INTO ACCOUNT BOTH COPPER AND IRON LOSSES

BY C. FORTESCUE

I. Introduction

When the temperature rise of a coil of copper wire is to be measured by the increase of resistance method, it is generally required that the calculated rise above actual room temperature be corrected to give the rise corresponding to a standard room temperature, *e.g.*, the rise which would have resulted if the room temperature were 25 deg. cent. It usually happens that the temperature of the room differs from the generally accepted standard of 25 deg. For this reason the rise in temperature is found under actual conditions of the test and then a correction is made, which depends upon the difference between the actual room temperature and the standard room temperature.

It is proposed in this paper to derive first of all an expression for the corrected temperature rise, for any arbitrary room temperature, of a body consisting mainly of copper, based on the assumption that the heat loss takes place mostly by convection, and that in comparison the amount lost by radiation is negligible. Lastly, an expression will be obtained for bodies consisting of both iron and copper immersed in a fluid medium which is cooled by air. It will be shown that with both iron and copper losses taken into account, the difference between the observed temperature rise and that corrected for the standard room temperature is very small, and even when convection alone is taken into account it may be considered, as a rule, negligible.

Within the ordinary range of temperatures, there is the same

increase in the resistance of a copper wire for each degree increase in temperature. The change in resistance caused by a change of one deg. cent., expressed as a fraction of the resistance at a definite standard temperature, is termed the temperature coefficient. The increase in resistance per degree is 0.00428 of the resistance at a temperature of zero deg. cent. Hence the resistance at any other temperature may be found by multiplying the number of degrees above zero by the coefficient and adding the result to the resistance at zero. The increase for each degree is 0.00386 of the resistance at 25 deg. cent. Therefore, the resistance at a higher temperature may be found by multiplying the number of degrees increase by this coefficient and adding the result to the resistance at 25 deg. These statements call attention to the difference between two coefficients which are in common use.

From the above definition of the temperature coefficient is derived the following well-known rule for calculating the temperature rise of a copper conductor above its initial temperature when the initial and final resistances are given, viz.:

$$t_2 - t_1 = \frac{R_2 - R_1}{R_1}(233.6 + t_1) \qquad (1)$$

where t_1 is the initial or room temperature, t_2 the final temperature and R_1 and R_2 the initial and final resistances.

II. Corrected Rise of Copper Conductors

The simple formula given below for determining the corrected rise of a coil carrying a current of constant value, is in its general form adapted to obtain the rise corrected for any arbitrary room temperature, when values of the initial and final resistance for any other room temperature are given. It is derived on the assumption that the rise in temperature above that of the surrounding air, of an air-cooled conductor carrying a given current, is proportional to the rate of dissipation of energy at the final temperature. The formula may be stated as follows:

$$t_b - t_a = \frac{R_2 - R_1}{R_1}(233.6 + t_a) \qquad (2)$$

where t_a is the arbitrary room temperature and t_b the temperature that would be reached by the apparatus if run in a room having

this temperature. The formula applies to naturally cooled apparatus consisting of copper conductors, provided that the effect of radiation can be considered negligible, but with proper modifications may also be used for artificially cooled bodies.

A simple statement of the formula, applicable to every room temperature, may be made as follows: If a number of similar coils of copper wire in rooms, kept at different constant temperatures, carry equal and constant currents throughout a heat run, and the temperature of each body and that of the room in which the run is made is, in each case, the same at the start, the percentage increase in resistance, when steady temperatures are reached, will be the same for each of the coils.

When the observed temperature rise under any condition of room temperature is given, that for any other room temperature may be found by the formula

$$t_b - t_a = (t_2 - t_1)\frac{233.6 + t_a}{233.6 + t_1} \qquad (3)$$

Here $(t_2 - t_1)$ is the observed rise for the test room temperature t_1, and $(t_b - t_a)$ is the corrected temperature rise based on a room temperature t_a.

Substituting 25 deg. cent., the A. I. E. E. standard room temperature, in equation (2), the following simple statement of the correction formula is obtained:

If the resistances are given,

$$\text{(temperature rise of body above standard room temperature)} = \text{(observed percentage increase in resistance)} \times 2.586 \qquad (4)$$

If the observed temperatures are given,

$$\text{(temperature rise of body above standard room temperature)} = \left(\frac{258.6}{233.6 + \text{observed room temperature}}\right) \times \text{(observed rise)} \qquad (5)$$

The derivation of formulas (2) and (3) is as follows:

From the assumed law of cooling, the following relations may be derived:

$$K(t_2 - t_1) = R_2 I^2 \qquad (6)$$

$$K(t_b - t_a) = R_b I^2 \qquad (7)$$

where K is a factor depending on the surface of the body and its heat conductivity, I is the current in the conductor and R_b is the final resistance corresponding to the temperature t_b.

From the definition given for temperature coefficient, it follows that

$$\frac{R_b}{R_2} = \frac{233.6 + t_b}{233.6 + t_2}$$

and therefore, by (6) and (7),

$$\frac{t_b - t_a}{t_2 - t_1} = \frac{233.6 + t_b}{233.6 + t_2}$$

$$= \frac{233.6 + t_b - (t_b - t_a)}{233.6 + t_2 - (t_2 - t_1)}$$

$$= \frac{233.6 + t_a}{233.6 + t_1}$$

whence is derived formula (3)

$$t_b - t_a = (t_2 - t_1)\,\frac{233.6 + t_a}{233.6 + t_1}$$

Substituting from (1), formula (2) is obtained.

$$(t_b - t_a) = \frac{R_2 - R_1}{R_1}\,(233.6 + t_a)$$

To illustrate this formula by an example, take the case of a body composed of copper wires run in a room whose temperature is 35 deg. cent. throughout the run; the observed final resistance when a steady temperature is reached is 20 per cent higher than the initial resistance; to determine its temperature rise corrected for a room temperature of 25 deg. cent.

Here the temperature rise obtained by test was 53.6 deg.

Applying formula (4), the corrected rise is found to be $20 \times 2.586 = 51.7$ deg. cent.

The above formulas have been derived on the assumption that

the rate of dissipation of heat from a body by convection is directly proportional to the difference in temperature of the body and the air. This law is commonly referred to as "Newton's law of cooling." If the effect of radiation is negligible and there is a free circulation of air, and its temperature is not raised appreciably after leaving the body, this law holds good. For bodies cooled by air flowing through constricted paths, such as air-cooled transformers, the average temperature of the coils will depend upon the average temperature of the air in the ducts, and the difference between these two values will depend upon the rate of dissipation of heat; but the average temperature of the air in the ducts, on account of the larger flow at the higher difference of temperature between coils and air obtained with higher room temperature, will not be proportional to the rate of dissipation of heat. In such cases the correction obtained by formula (**3**) will be too great.

The formulas (**2**) and (**3**) are suitable only for bodies whose external radiating surface is very small compared with the surface reached by convection currents. They will therefore apply to bodies cooled by forced convection. If the body is to be cooled by natural air circulation and has a smooth external blackened surface, so that the heat lost by radiation becomes appreciable, the formulas will give corrections very much too high, or even, in some cases, indicate a positive correction where it should properly be negative.

III. Corrected Rise Considering both Copper and Iron

It will be noted that the formulas which have been developed for obtaining corrected temperature rise by the increase of resistance method apply only to electrical apparatus composed wholly of copper conductors, or where the copper part of the apparatus may be considered separately from the rest on account of being heat-insulated from it. For air-cooled bodies consisting of both iron and copper, as, for instance, generators, it is very difficult to obtain a correction formula for room temperature; but in the case of apparatus in which both copper and iron are cooled by a common medium, such as oil, it is possible to obtain an approximate expression for corrected rise. Considering the case of oil-insulated air-cooled apparatus, such as oil transformers, let t_1 = initial room temperature, t_2 = final temperature of the copper, t_a = standard room temperature, t_c = corrected temperature. Let corresponding values of R be

designated by R_1, R_2 and R_b; let R_0 = resistance of body at 0 deg. cent., and let W be the iron loss. Then, approximately,

$$K\,(t_2 - t_1) = I^2 R_2 + W \tag{8}$$

$$K\,(t_b - t_a) = I^2 R_b + W \tag{9}$$

$$\frac{t_b - t_a}{t_2 - t_1} = \frac{I^2 R_b + W}{I^2 R_2 + W}$$

$$= \frac{\dfrac{I^2 R_0}{233.6}(233.6 + t_b) + W}{\dfrac{I^2 R_0}{233.6}(233.6 + t_2) + W}$$

$$= \frac{\dfrac{I^2 R_0}{233.6}[(233.6 + t_b) - (t_b - t_a)] + W}{\dfrac{I^2 R_0}{233.6}[(233.6 + t_2) - (t_2 - t_1)] + W}$$

$$= \frac{\dfrac{I^2 R_0}{233.6}(233.6 + t_a) + W}{\dfrac{I^2 R_0}{233.6}(233.6 + t_1) + W}$$

$$t_b - t_a = (t_2 - t_1)\,\frac{I^2 R_a + W}{I^2 R_1 + W} \tag{10}$$

This may be stated in the following words:

In air-cooled electrical apparatus composed of copper conductors and iron, immersed in a common medium, in which the copper carries a current of given value and the iron is subjected to a periodically changing induction of given magnitude, the temperature rise, when steady conditions are reached for any arbitrary room temperature, may be obtained from that calculated for any other room temperature, by multiplying this observed rise by the ratio of the total losses at the arbitrary and the given room temperature.

The observed rise at the room temperature of the test may be either that obtained by thermometer or by the increase in resistance method, using formula (1).

When it is desirable to obtain a closer approximation than that given above, the following procedure may be followed.

First, obtain the average temperature rise of the oil or common cooling medium above the test room temperature and correct to standard room temperature by formula (**10**). Next obtain the average rise of copper above the average temperature of the oil under test conditions and correct to the corrected oil temperature by equation (**3**); the sum of these two will give the temperature rise of the copper corrected to standard room temperature.

Applying the formula to a practical example—An oil-insulated air-cooled transformer has copper loss, at 25 deg. cent., 1000 watts, iron loss 1000 watts. At a room temperature of 35 deg. cent. the oil rose to an average of 25 deg. above the air. The average temperature of the copper above the oil was 15 deg. cent. What is the corrected average temperature rise of the copper at a room temperature of 25 deg. cent.?

Total loss at 25 deg. cent. = 2000 watts

Total loss at 35 deg. cent. = 2038 watts

$$\text{Corrected rise of oil} = \frac{I^2 R_a + W}{I^2 R_1 + W}(t_2 - t_1)$$

$$= \frac{2000}{2038} \times 25 = 24.5 \text{ deg. cent.}$$

Corrected average rise of coils above average temperature of oil

$$= \text{observed rise} \times \frac{233.6 + \text{corrected oil temp.}}{233.6 + \text{observed room temp.}}$$

$$= 15 \times \frac{233.6+49.5}{233.6+60} = 14.45 \text{ deg. cent.}$$

Corrected temp. rise of coils above air = 38.95 deg. cent.

The observed value was 40 deg. cent.

Thus, even when cooling by convection of air only is taken into account, the correction is so small as to be negligible in most cases. In fact, the correction is, as a rule, less than the probable errors in observation.

It has been assumed in the deduction of formula (**10**) that the average temperature rise of the oil is proportional to the total heat dissipated. This would be true only if the rate of flow of the convection currents of oil were constant. As a matter of fact, the oil will flow faster as the temperature rise of the coils above the oil increases. The flow will also be inversely proportional to the viscosity of the oil, which decreases as its temperature increases. The correction, therefore, given by the above rule, is always too great, and if, in addition, the heat lost by radiation on account of the higher coil temperatures reached with higher room temperature be taken into account, the correction will probably be reduced to zero, and, in some cases, instead of a positive correction as assumed in the rules, a negative correction may be necessary.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

THE TEMPERATURE RISE OF STATIONARY INDUCTION APPARATUS AS INFLUENCED BY THE EFFECTS OF TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY OF THE COOLING MEDIUM

BY J. J. FRANK AND W. O. DWYER

The proper correction to be applied to the temperature rise of apparatus when tested or operating under conditions differing from those which have been accepted as a reference standard has been investigated and discussed, and various conclusions drawn.

It is the purpose of this discussion to present a short theoretical resume of the considerations that enter into the above, together with the results of an investigation that has been made on some transformers under test to verify the conclusions which have been reached.

The room temperature to be considered as a reference standard as given in the Standardization Rules of the A. I. E. E. is 25 deg. cent., as stated in section 268, reading as follows:

"Room Temperature. The rise of temperature should be referred to the standard condition of a room temperature of 25 deg. cent."

The barometric pressure to be considered standard as given in the Standardization Rules of the A. I. E. E. is 760 mm. (29.92 in.) as stated in Section 270 and 271, reading as follows:

"Barometric Pressure. Ventilation. A barometric pressure of 760 mm. and normal conditions of ventilation should be considered as standard, and the apparatus under test should neither be exposed to draft nor enclosed, except where expressly

specified. The barometric pressure needs to be considered only when differing greatly from 760 mm.

"Barometric Pressure Correction. When the barometric pressure differs greatly from the standard pressure of 760 mm. of mercury, as at high altitudes, a correction should be applied. In the absence of more nearly accurate data, a correction of one per cent of the observed rise in temperature for each 10 mm. deviation from the 760 mm. standard is recommended. For example, at a barometric pressure of 680 mm. the observed rise of temperature is to be reduced by $\frac{760-680}{10} = 8$ per cent."

In artificially cooled apparatus no mention is made of the proper correction to be applied when the temperature of the cooling medium differs from the temperature of the enveloping air. In water-cooled apparatus no instructions are given for a standard reference temperature of the water. In apparatus cooled by air blast, no instructions are given in case the supply of air is taken from a source other than the room in which the apparatus is being tested.

No correction for changes in humidity is given.

General Theory of Dissipation of Heat from a Body

The rate of dissipation of heat from a body is dependent upon

1. Radiation
2. Convection
3. Conduction.

The transfer and final dissipation of heat is accomplished in several stages, each of which involves some or all of the above factors, *i.e.*, radiation, convection and conduction. We may roughly group the steps, in stationary induction apparatus, as follows:

a. From the core or from the conductor, through the insulation, to the cooling medium in contact with it.

b. Through the cooling medium to the case, tank or cooling coils.

c. Through the casing or cooling coils to the medium which finally carries away the heat.

Classification based on the several methods of cooling divides stationary induction apparatus into five groups as follows:

(i) *Self-Cooled Natural Draft.* In this class of apparatus the cooling is dependent upon (a) only. The heat is carried along

the conductor or through the conductor to its exposed portion by conduction, through the insulation by the same process, and dissipated by radiation and convection.

(ii) *Self-Cooled Oil-Insulated.* In this class of apparatus steps (a), (b) and (c) are involved. The transfer of heat is accomplished in this case by conduction through the insulation, convection and some radiation through the oil and convection and radiation from the tank.

(iii) *Artificially Cooled by Circulation of Oil.* In this class of apparatus steps (a), (b) and (c) are involved. The transfer of heat is accomplished by conduction through the insulation, convection and some radiation through the oil, and convection and radiation from (a) external radiators (b) water-cooled coils.

(iv) *Artificially Cooled Water-Cooled Apparatus.* In this class of apparatus the transfer of heat is similar to that in (ii) with the modification that most of the heat is carried away by convection by water circulated in cooling coils.

(v) *Artificially Cooled Air-Blast Apparatus.* In this class of apparatus the cooling may be dependent upon (a) only, where the air blast is in direct contact with the windings and core, or the cooling may be dependent on (a), (b) and (c), in such apparatus in which the blast of air comes in contact with the outside of the case or tank.

Radiation

The quantity of heat dissipated by radiation may be expressed by Stefan-Boltzman's law by

$$W_R = K\,(T_1^4 - T_2^4) \qquad (1)$$

where K = constant depending upon the diathermancy or transmissive power of the medium, upon the nature and color of the surface and upon the size of the enclosure in which body is dissipating heat.

T_1 = absolute temperature of the apparatus.
T_2 = absolute temperature of surrounding objects.

Convection

The calculation by mathematical considerations of the amount of energy dissipated by convection requires the use of one or more empirical constants. Much work along this line has been done by Prof. Kennelly and Dr. Langmuir, the results of the

latter's investigations being published in the *Physical Review* and the A. I. E. E. TRANSACTIONS.*

These investigations have been made for the most part on the dissipation of energy from fine wires at high temperatures where the amount dissipated by radiation is very small. Dr. Langmuir has shown, however, that in the dissipation from plane surfaces where the radiation factor is considerable the formulas developed may be used with excellent results.

Dr. Langmuir's theory is that the dissipation of heat by convection occurs by conduction through a film of adhering gas, the energy being conducted through this film by molecular diffusion to the moving convection currents of the surrounding gas and so carried away. Further, the results of his experiments show that the thickness of this film is constant (0.43 cm.) (for constant room temperature and pressure) and that the dissipation of energy by convection is almost entirely dependent upon the thickness of this conducting film.

While no data are given on the relative values of dissipation by convection from horizontal and vertical plane surfaces, the experimental values as obtained from wires show that the convection is somewhat less for vertical wires than for horizontal.

This difference will be more pronounced in case of plane surfaces, but the decreased efficiency will be more than compensated for by the flue or chimney action where the convection currents are constrained to move in restricted spaces such as ducts, corrugations, flues, etc. For this type of surface the effectiveness of dissipation by convection will probably be greater than for horizontal plane surface, provided that the surface does not become so complicated that friction will seriously affect the convection currents.

Assuming that the dissipation of heat by convection takes place by conduction through a film of adhering gas, Dr. Langmuir has developed a formula for this, of the form

$$W_c = \frac{\phi_1 - \phi_2}{B} = \text{watts dissipated per sq. cm.}$$

where B = thickness of adhering film and ϕ is a function of T of the form

$$\phi = 1.93 \times 10^{-5} (1 + 0.00012\, T) \left[2/3\, T^{3/2} - 248\, T^{1/2} + 124^{3/2} \tan^{-1} \sqrt{\frac{T}{124}} \right] \quad (2)$$

for air.

*TRANSACTIONS, A. I. E. E., 1912, XXXI, Part I, page 1229.

Conduction

Conduction consists of the transfer of heat from one part of one body to another part of same body or from one body to another without any bodily transfer.

The amount of energy transferred by conduction is proportional to the specific heat resistance, to the density of the heat flux and to the length of the path, *i.e.*, the rate of transmission of heat by conduction is proportional to the gradient or fall of temperature per unit length of path along the lines of flux flow.

$$W_d = \frac{K\,(T_1 - T_2)\,A\,t}{l} \text{ (for uniform gradient)} \qquad (3)$$

where t = Time
A = Area
l = Length
K = Conductivity

Effects of Temperature of Cooling Medium on Heat Dissipation

Section 269 of the A. I. E. E. Standardization Rules covers the correction to be applied to the temperature rise of apparatus when the reference temperature varies from 25 deg. cent. This rule reads:

"If the room temperature during test differs from 25 deg. cent., correction on account of difference in resistance should be made by changing the observed rise of temperature by one-half per cent for each degree centigrade."

The correction as applied means an increase of one-half of one per cent per degree in the observed rise when room is below 25 deg. cent. and a decrease of one-half of one per cent if the room temperature is greater than 25 deg. cent. The reference of 25 deg. cent. refers to a constant room temperature, a condition which is hard to maintain in practise. No provision is made for applying correction when room temperature is varying, or for correction for artificially cooled apparatus.

a. *Influence of Room Temperature on Radiation.* From equation (1) the quantity of heat dissipated by radiation from a hot body at temperature T_1 to surrounding objects at temperature T_2 is given by

$$W_R = K\,(T_1^4 - T_2^4)$$

It is apparent from the nature of the equation that W_R will increase with T_2 for a constant difference between T_1 and T_2 or in other words, for a given rise above room temperature, more watts will be dissipated the higher the room temperature, or the dissipation of a given quantity of heat by radiation will be accompanied by a less rise above room temperature the higher the room temperature.

Fig. 1 gives values of $T_1^4 - T_2^4$ for constant rises above different temperatures of surrounding objects. An inspection of these curves will show that for a 40-deg. rise at 0 deg. cent., $T_1^4 - T_2^4$ is 400×10^8, while for the same rise at 60 deg. cent. the value of $T_1^4 - T_2^4$ is 720×10^8, an increase of 80 per cent in the effective-

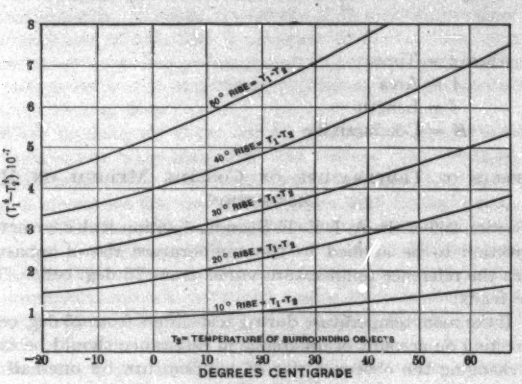


FIG. 1

ness of radiation. Consequently the same watts dissipated by radiation for a 40 deg. rise above 0 deg. cent. gives only a 24 deg. cent. rise at 60 deg. cent.

Fig. 2 gives the watts loss per sq. cm. dissipated by radiation for different rises above various room temperatures, assuming $K = 4.78 \times 10^{-12}$, *i.e.*, 90 per cent value of a perfect black body.

b. *Influence of Room Temperature on Convection.* The amount of energy dissipated by convection at constant room temperature (30 deg. cent.) is given in equation (2)

$$W_c = \frac{\phi_1 - \phi_2}{B} \text{ where } B = 0.43 \text{ cm.}$$

and

$$\phi = 1.93 \times 1.0^{-8} (1 + 0.00012\, T) \left[2/3\, T^{3/2} - 248\, T^{1/2} + 2 \times 124^{3/2} \tan^{-1} \sqrt{\frac{T}{124}} \right]$$

In Fig. 3, ϕ has been plotted against temperature. Now it has been found that while B is independent of temperature of body T_1 it varies with T_2, and Dr. Langmuir has found for free convection it is proportional to it, *i.e.*,

$$B_1 = B \times \frac{T_2}{T} \text{ where } B = 0.43 \text{ at 30 deg. cent.}$$

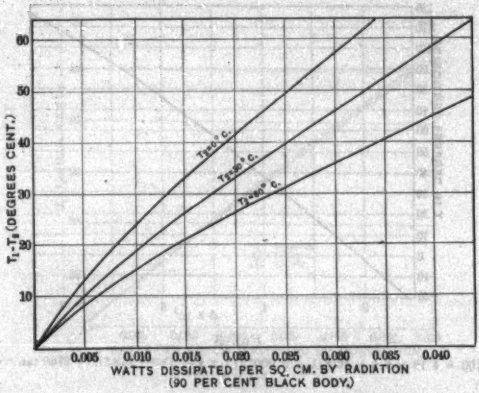


FIG. 2

Fig. 4 gives watts dissipated by convection for rises above various room temperatures. Unlike the dissipation by radiation, the energy dissipated by convection for a constant rise decreases with increasing room temperature, but to a much less extent, being almost independent of temperature.

In case of oil-insulated apparatus, convection also comes into play in the transfer of heat from the coils or core to the surface of the enclosing case or cooling coils. The process is no doubt similar to that for air, consisting in a transfer of heat through the adhering film of oil by conduction, and then by convection currents to the case, where a similar transfer takes place. The film

of oil is probably subject to same changes due to velocity and temperature as is the air film. Further, with increasing temperature the viscosity of the oil will change considerably, with a corresponding increase in velocity of convection currents. The net result of a higher room temperature on this step will be a more uniform distribution of temperature, so that while the top oil will be cooler and the bottom oil hotter, the average mean temperature will be lowered. This is shown in Fig. 6, while in Fig. 5 are given curves showing changes in viscosity with temperature of some transformer oils.

In connection with the effect of oil on temperature rise of ap-

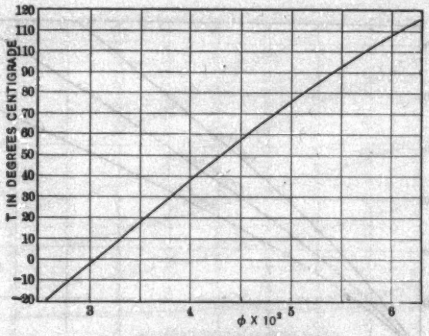


FIG. 3

$$\phi \times 100 = 4.19 \times 4.6 \times 10^{-4} (1 + 0.000127) \times \left(\frac{2}{3} T^{3/2} - 248 T^{1/2} + 2760 \tan^{-1} \sqrt{\frac{T}{C}}\right)$$

paratus it should also be noted that with increasing temperature the volume of oil and the wetted surface is increased. The linear expansion of transil oil may be expressed by

$$V_T = V_0 (1 + 0.000895\, T)$$

When V_T = Volume at temperature T

V_0 = Volume at deg. cent.

T = Temperature in deg. cent.

c. *On Conduction.* From equation (3) we had

$$W d = \frac{K (T_1 - T_2)}{l} A t$$

The transfer is inversely proportional to the resistance to the passage of heat.

Copper has practically no temperature coefficient for conduction, while the coefficient for iron is 0.00075.

Of the insulations, the conductivity of mica is unaffected by changes in temperature, while fibrous and cellulous materials such as are frequently used for turn and coil insulation, have a very considerable temperature coefficient, the thermal resistance being about 25 per cent less at 100 deg. cent. than at 0 deg. cent.

The effect of room temperature on conduction will in any case be small, but will always tend to decrease the resistance of this step with increasing temperature of room.

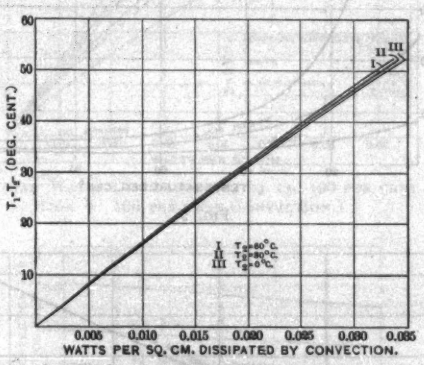


FIG. 4

The net effects of changes of room temperature on the dissipation of heat energy from stationary induction apparatus are

a. Effective radiation is greater the higher the room temperature.

b. The dissipation by convection in air is practically independent of room temperature. The transfer of heat by the convection currents in oil, immersed transformers will, however, be somewhat increased with higher room temperature.

c. Conduction will be better at higher room temperature.

CONSTANT LOSSES

For a constant loss we would expect, therefore, that apparatus would operate at a lower temperature rise the higher the tempera-

ture of the surrounding air. The actual change in rise will of course depend upon the proportion of losses dissipated by radiation and convection. In the case of dissipation from tank surfaces this proportion varies greatly with different styles of

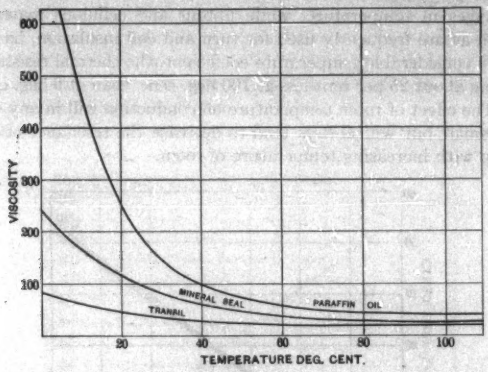


FIG. 5

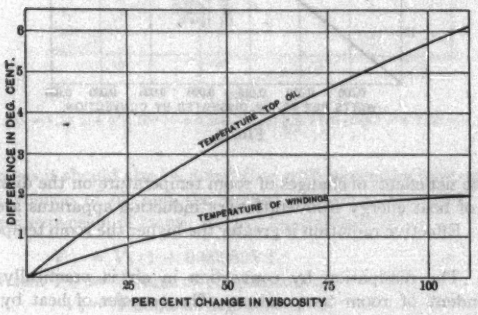


FIG. 6

tanks. The radiation value will be greatest on plain tanks, decreasing as the surface becomes more complicated by ribs, corrugations, flues, pipes, radiators, etc., the addition of which tends only to increase the convection component if the external dimensions remain the same.

In order to apply any correction to the emissive constants it is necessary to segregate the values for radiation and convection and apply to each separately.

Fig. 7 gives watts dissipated by various styles of tanks per square inch surface at 0 deg. cent. and 60 deg. cent., the percent-

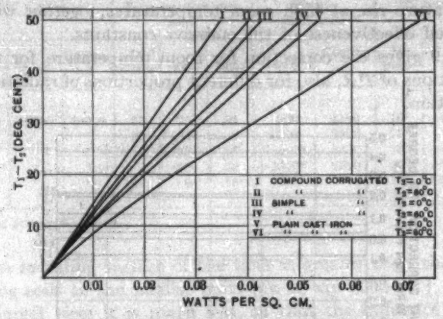


FIG. 7—TOTAL WATTS DISSIPATED PER SQ. CM. (90 PER CENT RADIATION + 100 PER CENT CONVECTION.)

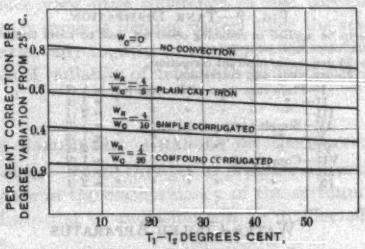


FIG. 8—TANK DISSIPATION

Corrections to be applied in reducing observed rises to room temperature of 25 deg. cent.—Constant losses.

When $T_2 > 25$ deg. cent. subtract correction.

When $T_2 < 25$ deg. cent. add correction.

age dissipation by radiation varying from 40 per cent to 16.6 per cent at 25 deg. cent.

Fig. 8 gives correction for temperature for constant losses for same tanks, to reduce to a standard reference of 25 deg. cent. room.

Increasing Losses

While the core loss is practically independent of the temperature, the load losses (I^2R) will increase with the temperature, due to the temperature coefficient of copper. This difference in I^2R amounts to 0.0042 per cent for each degree variation and allowance must be made for this increase in losses in determining temperature rise at high room temperatures, together with the increased effectiveness of the emissive constants.

Fig. 9 gives the correction for room temperature for various proportions of I^2R, also for different proportions of radiation and convection.

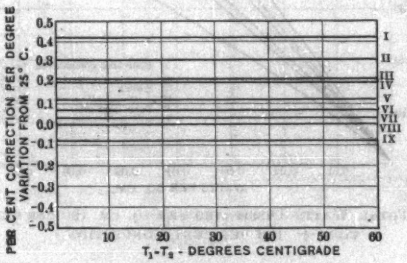


Fig. 9—Tank Dissipation.

Corrections to be applied in reducing observed rises to room temperature of 25 deg. cent.—Increasing losses with temperature.

When $T_2 > 25$ deg. cent. subtract correction.
When $T_2 < 25$ deg. cent. add correction.

I	Plain cast iron. I^2R: core loss	= 1 :2
II	" " " " " "	= 1 :1
III	" " " " " "	= 2 :1
IV	Simple corrugation. " "	= 1 :2
V	" " " " " "	= 1 :2
VI	" " " " " "	= 2 :1
VII	Compound " " " "	= 1 :2
VIII	" " " " " "	= 1 :1
IX	" " " " " "	= 2 :1

Water-Cooled Apparatus

This type of apparatus depends on the dissipation of heat by two factors, either of which may vary greatly in temperature. While the greater part of the heat is carried away by convection by cooling water, the dissipation from the tank may have a considerable influence on the temperature rise of such apparatus, as the table on the following page shows.

It is possible in the case of this class of apparatus, under certain conditions of temperature of room and ingoing water, to have the tank absorbing heat from the air while under test and contributing to a higher rise of the apparatus.

The surface of the cooling coils will usually approximate to that of the tank in area, but effectiveness of the cooling water is much superior to the air. Following is a table of rises with different temperatures of ingoing water and air temperatures:

Loss watts	Surface		Temperatures deg. cent.			Watts dissipated		Oil rises above		
	Tank	Cooling coil	In water	Air	Idler	Tank	Cooling coil	In water	Air	Idler
5000	10000	10000	25	25	25	900	4100	16°	16°	16°
"	"	"	25	0	8	2700	2300	13°	13°	30°
"	"	"	0	25	17	—400*	5400	18°	—7°	1°
"	"	"	0	50	33	—1800*	6800	20°	—30°	—13°
"	"	"	50	0	18°	4600	400	10°	60°	42°

*Heat absorbed by tank.

The radiating surface of the tank is greater than that of the cooling coils on the smaller units (up to say 1000 kw.), while on the larger sizes it is much less, so that the influence of room temperature will not be felt so much.

Changing from one temperature to another of ingoing water will introduce very little difference in rise (provided the air temperature is same as ingoing water) since the specific heat of water increases only slightly with temperature and the increased effectiveness of radiation of tank with temperature may be neglected.

Effect of Barometric Changes on Dissipation of Heat

a. *Radiation.* Since changes in pressure are unaccompanied by any change in the diathermancy of the surrounding medium the heat dissipated by radiation will be unaffected by changes in pressure.

b. *Convection.* It has been found that for constant room temperature, the energy dissipated by convection is proportional to B (thickness of film).

For free convection Dr. Langmuir's experiments show that the thickness of the adhering film varies with the 0.75th power of the pressure, while for forced convection this value was somewhat less. Using 90 per cent radiation value, the writers found the value for free convection to be somewhat less than this, being about the 0.64th power (free convection).

Fig. 10 gives watts dissipated by convection plotted against pressure for a 40 deg. rise at 25 deg. cent. using constant 0.75.

c. *Conduction.* This will be unaffected by changes in pressure.

The net result of a change in pressure of surrounding air on dissipation of energy from a heated body will be that with increased pressure a less rise will be experienced with constant losses.

The difference in rise with different pressures will of course depend, as it did in case of room temperature, on the proportion

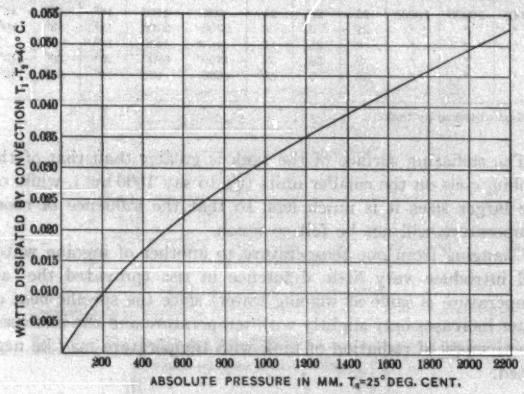


FIG. 10

of the emissive constants. Thus, apparatus having smooth contours, where the proportion of heat dissipated by radiation is a maximum, will be least affected by changes in pressure, while those with complicated contours will have a large correction for pressure.

The correction for room temperature will also vary with pressure, increasing with decreasing pressure. It is not possible to apply the same correction factor for room temperature at different atmospheric pressures.

AIR-BLAST APPARATUS

In this type of apparatus, the cooling of both core and coils is accomplished almost entirely by convection, the heat being

carried away by the convection currents caused by the blast. Very little heat will be dissipated by radiation from the windings, their insulation covering being at best a poor radiator, while the windings are generally so placed that what heat is radiated by one surface is absorbed by the next, and vice versa.

Air-blast apparatus is either rated for operation at a certain air pressure or with a certain volume passing through the coils per minute.

Where the rating is based on volume of air it is evident that the weight of air per cubic foot increases with the atmospheric pressure, decreases with the temperature and is practically independent of the quantity of moisture (except where fog-laden air is used). Since all the heat must be carried off by convection, it is evident that with increasing altitude or increasing temperature, the rise will increase for a constant volume of air passing through the ducts, the per cent increase being proportional to the temperature and inversely proportional to the pressure. It is probable that, as in the case for free convection, the correction for forced convection will vary more nearly as the 0.75th power which Dr. Langmuir found.

When the rating is based on air pressure, since the viscosity does not change with pressure, the same volume of air will pass through for the same difference in pressure, and correction will be the same as (1). The viscosity changes with the temperature, however, so that for the same pressure the volume will change with temperature while the specific heat will also change slightly with temperature. It should be expected, therefore, that since the viscosity varies as $T^{\frac{1}{2}}$ (approximately) and the weight as T^{-1} the weight per second would vary as $T^{-\frac{1}{2}}$ neglecting change in specific heat.

Fig. 11 gives corrections to be applied to the observed readings for variations in atmospheric pressure (constant temperature) for free and forced convection.

Fig. 12 gives correction to be applied to observed readings for variation in atmospheric temperature (constant losses) for forced convection.

Effect of Humidity Changes on Heat Dissipation

Radiation. Since water vapor is not perfectly diathermous, radiation from a heated body will be affected by its presence in the atmosphere surrounding the body.

While there is practically no absorption in dry air, the presence of water vapor does increase the absorption somewhat.

Investigators differ greatly in their estimates of the absorption of water vapor and its effect on radiation. While the heat absorbed by the vapor will increase the temperature of the air a small amount, it is evident that the effect on radiation will in any case be small, below saturation.

Convection. The presence of water vapor in the atmosphere will affect the quantity of energy dissipated by convection in so much as it affects the conductivity of the adhering film. We would expect, therefore, since the specific heat of water vapor is greater than dry air, that the conduction of the film B would be increased, and the effectiveness of dissipation by convection increased.

An inspection of Table III shows that for ordinary tempera-

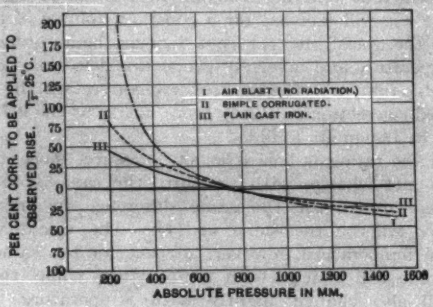


FIG. 11

tures and barometric pressures, even up to the saturation value, the percentage of moisture compared to air (by weight) is very small, amounting at most to a few per cent, so that it can have very little effect on the convection value. The values as obtained by experiments seem to verify this, the difference in rises with varying percentage of moisture being entirely negligible.

In the case of fog-laden air where particles of water are actually present, the case is very different, and a very considerable correction would have to be made.

EXPERIMENTAL OBSERVATIONS

Tests were made on two duplicate standard lighting transformers (oil-insulated, self-cooled), with losses within ½ of 1

per cent of each other. It was necessary to increase the losses above normal so as to obtain a 40-deg. rise by oil. This increase in losses was accomplished by holding over-load current, but normal excitation.

Heat tests were conducted in large pressure tanks, one transformer being placed in each tank, as shown in Fig. 16. The transformers were placed on wooden tables resting on the bottoms of the tanks, the tops of the tables being nearly same area as base of transformer cases. Tanks were supplied with radiating coils connected to a steam and water source. An insulating asbestos shield was placed over the cooling coils so as to protect the transformers from their direct radiation.

Both tanks were provided with chloride driers through which

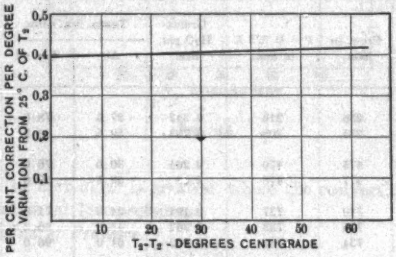


FIG. 12—CORRECTION FOR AIR-BLAST APPARATUS ONLY—ASSUMING CONSTANT LOSSES.

When $T_2 > 25$ deg. cent. add correction.
When $T_2 < 25$ deg. cent. subtract correction.

air could be introduced under a pressure. In addition, vacuum connection could also be made.

The system of switching was so arranged that when the heat run was interrupted resistance measurements could be quickly taken.

Temperatures were taken by means of generator bulb thermometers read directly from a central dial while run was on. The thermometers were placed as in Fig. 16, check thermometers being used at the more important places. In addition, wet and dry bulb check readings were taken by spirit thermometers.

Very little heat was conducted from the transformer tank to the cover, as a gasket of felt packing was placed between them. The temperature of the cover was very little above the surround-

ing air, so it was neglected in calculating radiating surface. Since the base rested on a wooden table, practically no heat was conducted from it. The total wetted surface at 25 deg. cent. was 6620 sq. cm. which corresponds to a radiating surface on outside of tank of 7020 sq. cm. The actual effective surface due to conduction to unwetted portion will be greater than this, and in this case equal to 8500 sq. cm.

Further, the temperature of the case was different at different heights, being a maximum at top oil level, and decreasing toward top and bottom, the bottom temperature being less, the less the viscosity of the oil. To reduce to effective temperature for the whole tank it would be necessary to integrate from top to bottom.

TABLE I

Watts loss	Press. in mm.	$P - 0.378\,E$ in mm.	Grains H_2O per liter	Temp. deg. cent.		Rise deg. cent. top oil
				Air	Top oil	
422	236	216	0.342	27.5	78.0	50.5
437	235	208	0.703	59.0	99.2	40.2
423	475	470	0.264	30.0	76.0	46.0
436	477	470	2.11	59.5	98.0	38.5
422	740	737	0.194	24.5	71.4	41.9
435	735	733	0.362	45.0	86.3	41.3
440	734	731	0.622	61.0	96.0	35.0
420	1245	1233	0.292	26.0	66.0	40.0
435	1244	1231	0.565	61.0	93.0	32.0
413	1780	1772	0.256	26.5	63.0	36.5
435	1778	1770	1.44	59.5	91.5	32.0

In the present case, we have taken average temperatures, which will probably be sufficiently close.

Test Observations

I. *Readings taken to Determine Effect of Temperature of Surrounding Air.* Corrections made in pressure readings for elastic vapor pressure E of the water vapor present according to

$$P = P_1 - 0.378\,E$$

P = Calculated pressure in mm.
P_1 = Observed " " "
E = Elastic vapor pressure in mm.

Fig. 13 gives curves of the above with values in Table I (neglecting humidity), plotted with observed values and also corrected for constant losses. As would be expected from the previous dis-

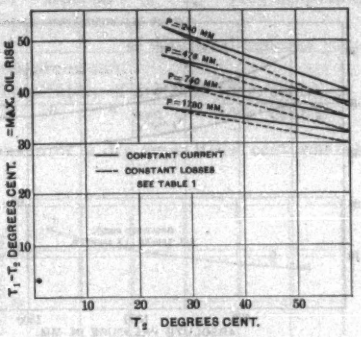


FIG. 13

cussion, the correction is greatest where the convection value is least, that is, at low pressures.

II. *Effect of Pressure.*

TABLE II A

Watts loss	Press in mm.	P — 0.378 *E* in mm.	Grains H_2O per liter	Temp. deg. cent. Air	Temp. deg. cent. Oil	Rise deg. cent. top oil
422	236	224	0.077	29.0	80.0	51.0
423	358	355	0.099	29.5	78.0	48.5
423	475	471	0.117	28.2	75.5	47.3
420	734	732	0.176	30.0	71.8	41.8
415	1252	1245	0.236	29.6	69.5	40.0
410	1780	1774	0.256	26.5	63.0	36.5
410	2280	2273	0.301	25.0	59.0	34.0

TABLE II B

438	236	210	0.705	59.0	99.2	40.2
437	476	470	2.08	59.5	98.0	38.5
435	731	731	0.622	61.0	96.0	35.0
433	1248	1237	0.565	61.0	93.0	32.0
432	1780	1774	1.44	59.5	91.5	32.0

Fig. 14 gives curves plotting temperature rise against pressure for 30 and 60 deg. cent. room temperature.

Heat tests were also conducted on three 125-kw. self-cooled, oil-insulated transformers assembled in simple corrugated tanks

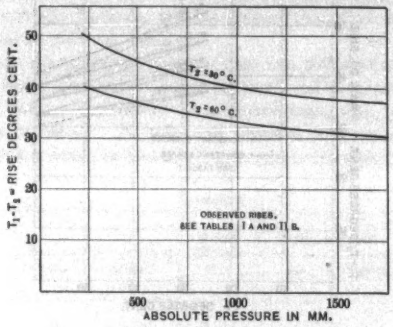


FIG. 14

at Schenectady, Pittsfield, Grand Junction, Colo., and Leadville, Colo., to determine what effect the altitude had on heating. Following is a summary of the tests made.

TABLE II C

Place	Watts loss	$P - 0.378\ E$	Grains H_2O per liter	Oil rise deg. cent.
Schenectady.....	4820	758	0.151	36.0
Pittsfield.....	4820	732	0.116	37.5
Grand Junction..	3965	631	0.202	32.5
Leadville.....	4570	518	0.197	39.6

Reduced to same loss the rises are given in Fig. 15 and Table II D.

TABLE II D

Place	Watt loss	P. 0.378 E	Grs. H_2O per liter	Oil rise deg. cent.
Schenectady.....	4820	758	0.151	36.0
Pittsfield.....	4820	732	0.116	37.5
Grand Junction.....	4820	631	0.202	39.5
Leadville.....	4820	518	0.197	44.0

III. *Effect of Humidity.* Humidity measurements were taken by wet and dry bulb thermometers, the elastic force of the vapor being calculated according to formula.

$$E = E_1 - 0.00066\, P\, (t - t_1) \quad \{1 + 0.00115\, (t - t_1\}$$

where E = Vapor pressure in mm.
E_1 = " " of saturated aqueous vapor.
P = Pressure in mm.
t = Temperature of dry bulb (deg. cent.)
t_1 = " " wet " (deg. cent.)

Weight of one liter of dry air at 0 deg. cent. was taken as 19.52

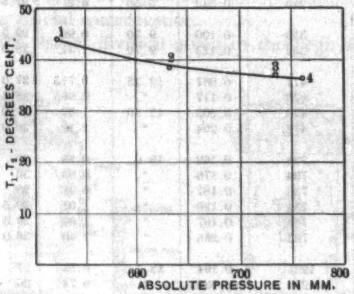


FIG. 15

Altitudes.
1. Leadville, Colo. ..... 3190 m.
2. Grand Junction, Colo. ..... 1525 m.
3. Pittsfield, Mass. ..... 346 m.
4. Schenectady, N. Y. ..... 75 m.

Observed rises on 125-kw. transformer, reduced to constant losses.

grains. Correction for vapor pressure was applied to observed pressures according to the formula

$$P = P_1 - 0.378\, E$$

where P_1 = Observed pressure.
E = Elastic vapor pressure
P = Calculated pressure.

Weight of dry air in one liter of air was calculated from

$$W = \frac{P - 0.378\, E}{29.92} \times 19.52 \text{ grains}$$

Weight in grains of water present in one liter of air was calculated from

$$W_1 = \frac{62.3 \times E}{29.92 - E} \times \frac{P - 0.378\,E}{P} \times 0.1952 \text{ grains}$$

TABLE III

Watts	Pressure	$P - 0.378\,E$	Grs. H_2O per liter	Grs. dry air per liter	Per cent moisture by wt.	Temp air.	Temp top oil	Rise top oil
422	236	234	0.078	5.65	1.3	29.0	80.0	51
"	"	232	0.156	5.62	2.6	27.5	78.5	51
"	"	216	0.342	5.50	6.2	27.5	78.0	50.5
422	358	353	0.100	9.70	0.99	29.5	78.0	48.5
"	"	352	0.123	9.70	1.31	28.0	76.5	48.5
422	475	471	0.087	12.15	0.715	27.0	74.5	47.5
"	477	473	0.117	"	0.965	28.2	75.5	47.3
"	477	473	0.202	12.10	1.67	27.0	74.0	47.0
"	476	472	0.204	"	2.19	30.0	76.5	46.5
420	735	733	0.162	19.0	0.86	30	71.3	41.3
"	736	734	0.176	"	0.93	30	71.8	41.8
418	734	733	0.187	"	0.98	28	69.3	41.3
420	734	734	0.190	"	1.01	30.5	71.8	41.3
"	737	736	0.197	"	1.04	29.5	71.4	41.9
"	735	733	0.265	"	1.40	30.0	72.0	41.5
417	1233	1231	0.194	32.1	0.55	27	66.0	39
"	1241	1236	0.236	"	0.74	26	66.0	40
418	1238	1235	0.292	"	0.91	29.5	69.5	40
414	1780	1776	0.256	44.8	0.57	26.5	63.0	36.5
413	1778	1774	0.278	"	0.62	24.0	60.0	36.0

Conclusions

Referring to Figs. 13 and 14 and Table III, it will be seen that the temperature rise of apparatus varies inversely with the temperature, inversely with the pressure and is practically independent of the water vapor over the ranges covered by test. The variations due to changes in amount of water vapor were small, and the results almost invariably showed the same rises for different quantities of water vapor present. This is to be expected, as a glance at Table III shows that even at saturation and moderate temperatures, the percentage of moisture is very small and can have little effect on the heat dissipation by convection or on the dissipation by radiation due to the change in diathermancy. With fog-laden air, *i. e.*, where particles of water

are held in suspension, the case is very different, the water now being a much greater proportion by weight of the mixture, the dissipation by convection being greatly increased, while no doubt the dissipation by radiation will be somewhat diminished. The exact correction to be applied in any case will of course depend upon the proportion of heat dissipated by convection and radiation, which in turn depends upon the type of apparatus and means of cooling.

Recommendations

It is evident from the above discussion that the corrections to be applied for variations in atmospheric conditions are not the same for different types of stationary induction apparatus, each type requiring special consideration.

Following the line of division given in the beginning of this

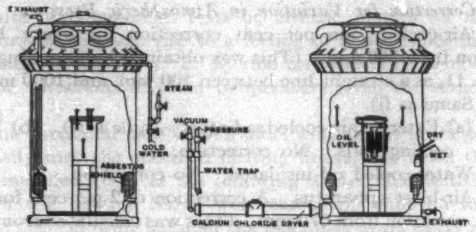


Fig. 16

(Both tanks are arranged alike.)

paper, it is recommended that the following corrections be made and precautions taken:

I—*Corrections for variation in room temperature.*

(i) Air-cooled natural draft—no correction.

(ii) Self-cooled oil-insulated—no correction.

(iii) Forced oil circulation—no correction.

(iv) Water-cooled apparatus—no correction, but precaution should be taken to have the ingoing water at as nearly as possible the same temperature as the room, which should be as near 25 deg. cent. as possible.

While in (i), (ii) and (iii) there will be a correction for variation in room temperature from standard, this correction will depend entirely upon the relative effectiveness of the emissive factors, and in order to apply any such correction accurately it

would be necessary to divide such apparatus into a large number of groups. It is safe to assume that the increased losses will be about compensated for by the increased effectiveness of dissipation and make no corrections whatever.

Of course, wherever possible, the apparatus should be tested under the same conditions as it is to operate under, or under conditions as nearly as possible approaching these.

(v) Air-blast apparatus. A correction of ½ of one per cent per degree variation from 25 deg. cent., the correction to be added to the observed; use when the reference temperature is below 25 deg. cent. (This correction is based on ratio of core loss to copper loss of 1:1 and on all the heat being dissipated by convection).

The reference temperature in this class of apparatus to be temperature of ingoing air where this differs from temperature of room in which apparatus is operating.

II—*Correction for Variation in Atmospheric Pressure.*

(i) Air-cooled, one per cent correction for every 10 mm. variation from 760 mm. (This was obtained by assuming curve II, Fig. 11, as a straight line between 400 mm. and 1000 mm.).

(ii) Same as (i).

(iii) (a) External air-cooled radiators—same as (i). (b) Water-cooling coils. No correction.

(iv) Water-cooled oil-insulated. No correction.

(v) Air-blast apparatus. A correction of 2 per cent for every 10 mm. variation from 670 mm. (This was calculated from curve III, Fig. 11, assuming it to be a straight line between 400 mm. and 1000 mm.).

III—*Correction for humidity variations in atmosphere.*

(a) At and below saturation at ordinary room temperatures, no correction need be made for moisture.

(b) When fog-laden air is used the apparatus should be given a special rating, the specifications covering temperature rise when operating under such conditions.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

EFFECT OF ROOM TEMPERATURE ON TEMPERATURE RISE OF MOTORS AND GENERATORS

BY MAXWELL W. DAY AND R. A. BEEKMAN

Results of commercial tests on electric motors for the last few years, have given rise to a feeling of doubt concerning the correctness of the A. I. E. E. rule for correcting temperature rises for variations of room temperature from the standard of 25 deg.

In one particular case some motors were tested in the summer and easily met the specified heating limits, but when the customer installed them in the following winter, and tested them, some of the heating limits were exceeded, while on retesting them in the following summer the machines again easily met the specifications.

Arrangements were made, therefore, during the following winter, to test an enclosed motor in a room, the temperature of which could be controlled, and this motor was run for one hour, and also continuously at the following room temperatures: slightly below zero, 25 deg., and 30 deg. The results are given in Figs. 1 and 2, and show that the temperature rises in the cold room were, in most cases, more than those in the hot room. These figures show values of the rise on the different parts of the machine, with the ones obtained at the same room temperature joined by straight lines. Thus the slope of the lines is indicative only of the relative rises of the different parts under the same conditions, while the positions of the lines on the temperature scale show the relative rises under the different conditions, which is the object of our investigation.

These results seem to be reasonable, in view of the Stefan and

Boltzmann law that the radiation of heat is proportional to the fourth power of the absolute temperature. This law seems to have been ignored in many cases, but was discussed by Dr. Goldschmidt in his paper "Die Grundgesetze der Erwaermung elektrischer Maschinen", published in *Elektrotechnische Zeitschrift*, of Sept. 10 and 17, 1908.

This same subject is treated further by Dr. Ludwig Binder in "Ueber Waermeuebergang auf ruhige oder bewegte Luft", published in 1911, in which he shows that the radiation of heat

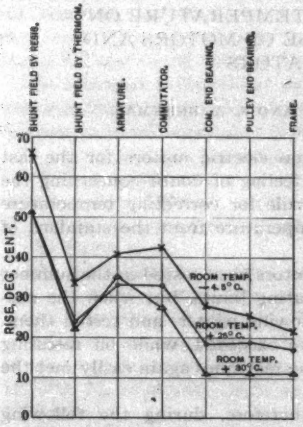


FIG. 1 — TOTALLY ENCLOSED MOTOR, 30 H.P., 550 REV. PER MIN.—52 AMPERES, 500 VOLTS—ONE-HOUR RUN.

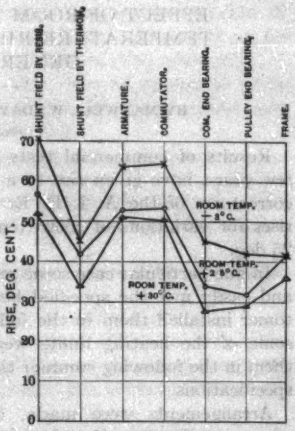


FIG. 2 — TOTALLY ENCLOSED MOTOR, 30 H.P., 550 REV. PER MIN.—30 AMPERES, 400 VOLTS—CONTINUOUS RUN.

increases 1.2 per cent for each degree of room temperature above ice zero, and 0.62 per cent for each degree of difference of temperature between motor and room. The radiation per degree difference between the motor and the room is 1.85 times as much with a room temperature of 20 deg. and a motor temperature of 100 deg., as if the room were 0 deg. and the motor one deg.

However, only a portion of the heat is carried away by radiation, as natural convection and forced ventilation must also be considered.

Considering the fact that a few tests, already made, indicated the incorrectness of the A. I. E. E. correction rule, which tests were confirmed by the papers mentioned, it was thought desirable to make some careful tests under conditions in which the room temperature could be controlled through a considerable range, and also to consider results already obtained on a large number of commercial tests, which might be comparatively inaccurate individually, but it was thought that with a sufficient number a definite tendency could be discovered.

It was not thought desirable, in the time available, to make a thoroughly scientific investigation to determine a new rule for temperature correction nor to determine the physical causes for these differences, but it was thought that some definite data could be obtained, which would be of interest in determining whether the present correction rule should be followed in the future, leaving for the future the scientific determination of a revised rule.

No attempt has been made in the following, to determine the effect of barometric pressure nor of humidity, although readings were taken during the special tests, but it is understood that moisture in the air in the form of vapor has but little effect on the temperature rises, although moisture in suspension, which is not evaporated before coming in contact with the machine, considerably reduces the temperature rise by absorbing heat from the machine through evaporation.

In the following we will first describe the special tests made in the enclosed room to determine the effect of room temperature, and later will give an analysis of a number of commercial tests made during the last few years.

Description of Special Tests

The special tests were run on two different types of direct-current motors. In each case the machine was a shunt motor with commutating field. The first set of tests was run on a motor rated at 7½ h.p., 825 rev. per min., with a normal current rating of 28.5 amperes. In the second set the motor was rated as 20 h.p., 700 rev. per min., with a normal current rating of 75 amperes.

In each case the normal voltage, 230, was held on the motor armature and commutating field in series, and also across the shunt field. The input into the motor was held constant at two values for each machine, viz.: 28.5 and 14.25 amperes for

the first set of tests, while 75 and 37.5 amperes were the values for the second set. The conditions under which these two values were held will be given later.

The tests were run in a room approximately 16 by 14 ft. (4.9 by 4.3 m.). (See Fig. 3). Within this room is located an oven generally used for baking coils, the size of which is approximately 11 by 7 ft. (3.4 by 2.1 m.). In this oven are iron pipes, through which steam is ordinarily passed to gain high temperature. These coils were used in these tests for both heating and cooling purposes. In heating, steam was passed through them; in cooling, city water, at a temperature of approximately 13

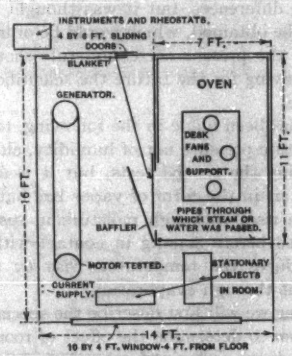


FIG. 3.—SKETCH OF TEST ROOM.
Brick walls—corrugated sheet iron ceiling—height of room 8 ft.

deg., was used to keep the room temperature as low as possible. Air was kept moving past these coils by the use of three ordinary desk fans.

This oven has a sliding door about 4 by 6 ft. (1.2 by 1.8 m.) and in the case of the hot room test the temperature of the room proper was maintained very close to 45 deg. by means of regulating the opening of this oven door. Between the motor under test and the oven door a wooden baffler was placed, in order to prevent any direct currents of air from the oven playing upon the motor.

Access to the room is obtained by means of a second sliding door of the same size as that of the oven. This door was kept

closed throughout the test, except when it was necessary for the men to pass in and out. In order to prevent this passing in and out from affecting the temperature of the room a blanket was hung in front of the door, and so arranged that the openings were "staggered". The room contains one large window, approximately 10 by 4 ft. (3 by 1.2 m.), reaching from the ceiling to within 4 ft. (1.2 m.) of the floor; this window is of ground glass and was kept closed throughout the tests.

The apparatus used in testing, located in the room, consisted of the motor under test belted to a generator for load, starting box, circuit breakers, and of course, thermometers. The rheostats and instruments were placed outside of the room, so that no heat was developed in the room, except the losses of the motor and generator. There are some stationary objects located in the room, consisting chiefly of wood.

Due to the fact that no convenient place could be obtained for conducting these tests near a suitable direct-current generator, from which constant voltage could be obtained, it was necessary to run the test motor from the 250-volt shop circuit. It was found by a preliminary record of a recording voltmeter, that this voltage varied at times, by an amount as great as 20 volts. It was therefore necessary to take steps to maintain constant voltage on the motor. This was done by placing a rheostat in series with the motor and the supply. This rheostat was, as stated above, placed outside of the room and was of the type which is controlled remotely by solenoids. The control for this rheostat was placed directly on the testing table by the voltmeter indicating the motor voltage, and for part of the tests a man was kept constantly varying this in order to hold the rated (230) volts on the motor. For the remainder of the tests, however, a contact-making voltmeter was used to control the solenoids on the rheostat, and thus maintain constant voltage.

Besides the original indicating voltmeter record, a recording voltmeter record of the motor voltage was obtained during those tests in which manual control was used. This compelled constant attention on the part of the test men, and hence insured more accurate results.

As stated previously, in the case of the hot room tests the room temperature was maintained very nearly constant at 45 deg., but in the case of the cold room test our object in each case, was to have as cold a room temperature as possible after the temperatures had become constant; *i.e.*, when the heat run was

ready to be taken off. Hence, while in the hot room test the room temperature was constant almost from the first, this is not true in the cold room test; but the temperature of the room rose, due to the losses of the motor and generator, until at the end, when constant conditions were obtained, it was usually considerably higher than at the beginning of the test.

It was found, by comparing the thermometers, that they differed considerably one from the other, and hence all were calibrated with two which read alike, chosen as standard. In order to eliminate the necessity of applying a correction to each thermometer reading, the same thermometers were used to read temperatures on the same parts of the machine throughout the test. In the case of the thermometers on the stationary parts, nearly all were left in the same positions from the start; the only ones removed were those on the pulley end shield and these were removed only when conditions were changed by removing the fan. In placing the thermometers on the rotating parts at the end of the run the same thermometers were also used, and the men attempted to place these exactly in the same positions.

The instruments used in the test were carefully calibrated before and after the runs, and practically no change was found, so that the relative readings were accurate.

The tests on the 7½-h.p. motor were run under six conditions:

1. Open motor with fan; that is, the motor was provided with a fan on the pulley end and the commutating end completely open to the air.

2. Open motor without fan. In this case the motor was exactly the same, except that the fan on the pulley end was removed.

3. Semi-enclosed motor with fan. Under these conditions, with a fan on the pulley end, a ventilating cover was placed over the commutating end.

4. Semi-enclosed motor without fan. The fan was removed and the same ventilating cover was used as in the preceding.

5. Totally enclosed motor with fan. In this case the ventilating cover was replaced by a totally enclosing cover and the openings in the pulley end shield were closed.

6. Totally enclosed motor without fan. The conditions were the same as in the fifth run except with the fan removed.

The tests on the 20-h.p. motor were run only under three of the above conditions, viz.: first, third, and fifth; in other words, in the case of the latter motor we did not remove the fan.

The input into the 7½-h.p. motor was held at 28.5 amperes during the tests run under the first four conditions and at 14.25 amperes during those run under the last two, as the temperatures would have been dangerously high had the normal rated current been held when running as a totally enclosed machine. The input into the 20-h.p. motor was held at 75 amperes during the tests run under the open and semi-enclosed conditions, and at 37.5 amperes during those run under the totally enclosed conditions.

It was the original intention to run four tests under each of the different conditions, two at the cold room and two at the hot room temperature. The check tests at the same conditions were really the same tests with a short interval of time between. That is, the motor was run under one fixed condition until the temperatures were constant; it was then shut down and final readings taken. Then it was immediately started up and the check run put on under the same condition.

This plan was followed, giving 24 tests on the 7½-h.p. motor, and at the end, due to the confusing results on the open motor with fan and the semi-enclosed motor without fan, it was thought necessary to repeat the tests under these conditions. In the case of the open motor with a fan all four tests were repeated, but in the case of the semi-enclosed motor without fan only three check tests were run, because the results of the third at the hot room temperature checked very closely with the two previous ones.

The list of the tests made on the 7½-h.p. motor is as follows:

	Hot room	Cold room
Open motor with fan	4 runs	4 runs
Open motor without fan	2 runs	2 runs
Semi-enclosed motor with fan	2 runs	2 runs
Semi-enclosed motor without fan	3 runs	4 runs
Totally enclosed motor with fan	2 runs	2 runs
Totally enclosed motor without fan	2 runs	2 runs

The list of the tests made on the 20-h.p. motor is as follows:

	Hot room	Cold room
Open motor with fan	2 runs	2 runs
Semi-enclosed motor with fan	2 runs	2 runs
Totally enclosed motor with fan	2 runs	2 runs

At the beginning of the tests great care was taken in measuring the cold resistance of the shunt fields. The readings were taken after the motors had been in the room a long enough time to allow the temperatures on the motor parts to become the same as that of the room. These cold resistance readings were taken on different days, at different room temperatures. The results, from which the resistance at 25 deg. was calculated, checked within 0.3 of one per cent.

In every case the heat runs were continued until the field readings showed a constant resistance for at least two hours, and the thermometers on the different parts also showed constant temperatures throughout the same period.

Precautions. Following are given precautions which were taken to secure accurate results and obtain as nearly as possible laboratory conditions. Some of these precautions have been given in the description above, but it is thought best to repeat them under this heading.

1. Recording voltmeter record of the motor voltage was kept.
2. Precautions were taken to eliminate drafts and sudden changes of room conditions.
3. Thermometers were kept in the same relative positions.
4. The data for any one run were immediately taken from the men running the test, so that their readings during the check run would not be influenced by their knowledge of values previously obtained.
5. The instruments were calibrated before and after the tests to determine if any change had taken place in their errors.
6. The same men performed the same tasks, such as reading the thermometers, and regulating the voltage, in order to eliminate, as far as possible, personal errors.
7. All final temperature readings were taken by the same men; that is, no run was taken off by the night force.
8. Four thermometers were read in different positions in the room, relative to the motor, two being directly in the open air and two being immersed in oil.

Results

Special Test. Figs. 4 to 12.

A. 7½-h.p., 825-rev. per min., 230-volt, 28.5-ampere motor.

1. Open motor without fan. Run at rated load until conditions were constant. Two runs at 23 deg. room temperature; one at 44 deg. and one at 45 deg.

Looking at Fig. 4, the results are plotted in the same way as in Figs. 2 and 3. We have averaged the results for the cold room runs and also for the hot room runs, inasmuch as the different tests under these conditions varied only a very little

in the value of room temperature, and it was thought that an average of the rises would mean more than curves with check points plotted on them. The same applies to the remaining curves for the special tests.

All parts show lower rise at hot room temperature, except the commutator, which became quite rough between runs.

Correction to be applied to the rise per degree difference of room temperature from 25 deg. varies from −0.193 per cent to −0.754 per cent, for the different parts of the machine. The minus sign is used to indicate those corrections which show a

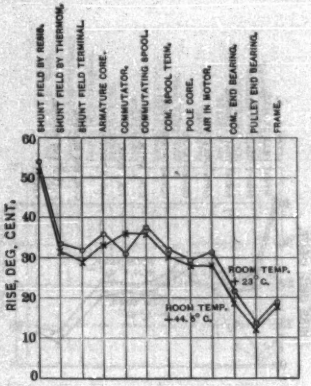


FIG. 4—OPEN MOTOR WITHOUT FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

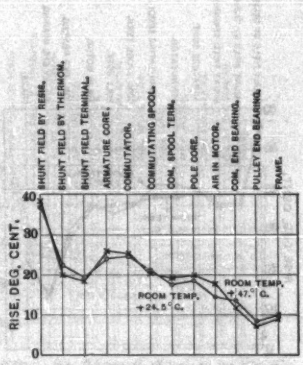


FIG. 5—OPEN MOTOR WITH FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

lower rise at hot room temperature, and a positive sign the opposite. These signs are assigned on the basis of the slope of the curve of rise against room temperature.

2. Open motor with fan. (See Fig. 5.) Run at rated load until conditions were constant. Three runs at practically 24 deg.; one at 26 deg.; two at 44 deg. and one at 47 deg. Results not in the same direction for the different parts.

Shunt field by resistance.....	Inconsistent
Shunt field by thermometer.....	Rise less at hot room temp.
Armature core and conductor....	Inconsistent.
Commutating spool.....	Inconsistent.

Commutator	Inconsistent.
Pole core	Inconsistent.
Frame	Inconsistent.
Pulley end bearing	Inconsistent.
Commutator end bearing	Rise less at hot room temp.

By "inconsistent" is meant that results point in no definite direction, due, probably, to difference between actual temperature rises being less than experimental error.

Corrections not calculated.

3. Semi-enclosed motor without fan. (See Fig. 6.) Run at rated load until conditions were constant. Three runs at

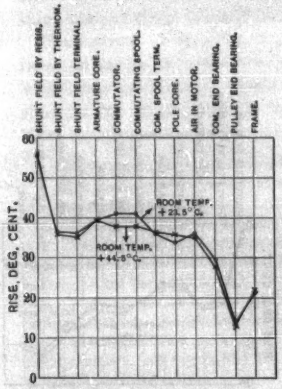


FIG. 6—SEMI-ENCLOSED MOTOR WITHOUT FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

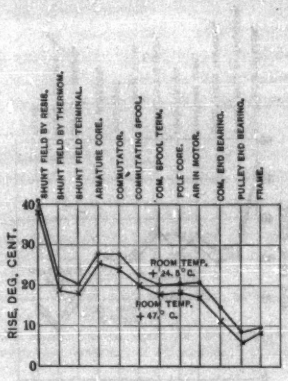


FIG. 7—SEMI-ENCLOSED MOTOR WITH FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

practically 24 deg.; one at 23.5 deg.; two at practically 44 and one at 45 deg. Results not in the same direction for the different parts.

Shunt field by resistance	Inconsistent.
Shunt field by thermometer	Inconsistent.
Armature core	Inconsistent.
Commutating spool	Rise less at hot room temp.
Commutator	Inconsistent.
Pole core	Rise less at cold room temp.
Frame	Inconsistent.
Pulley end bearing	Inconsistent.
Commutator end bearing	Rise less at hot room temp.

Corrections not calculated.

4. Semi-enclosed motor with fan. (See Fig. 7.) Run at rated load until conditions were constant. Two runs at practically 25 deg.; one at 47; one at 47.5. All parts show lower rise in hot room.

Correction to be applied to rise per degree difference of room temperature from 25 deg. varies from −0.216 per cent to −1.36 per cent.

5. Totally enclosed motor without fan. (See Fig. 8.) Run at one-half rated load until conditions were constant. Two runs at practically 20.5 deg. and two at practically 45 deg. All parts show lower rise at hot room temperature.

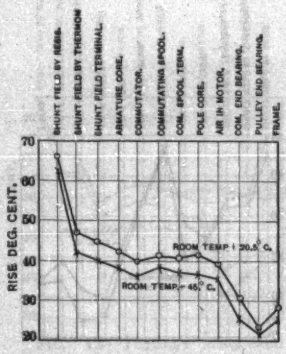


FIG. 8—MOTOR TOTALLY ENCLOSED WITHOUT FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

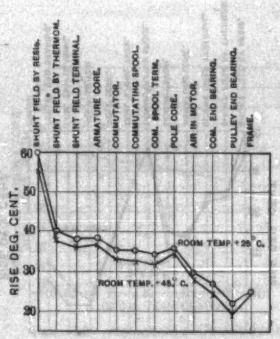


FIG. 9—MOTOR TOTALLY ENCLOSED WITH FAN—7½ H.P., 825 REV. PER MIN., 230 VOLTS.

Correction to be applied per degree difference of room temperature from 25 deg. varies from −0.233 per cent to −0.785 per cent.

6. Totally enclosed motor with fan. (See Fig. 9.) Run at one-half rated load until conditions were constant. Two runs at 25 deg.; two at 45 deg. All parts show lower rise at hot room temperature.

Correction to be applied to rise per degree difference of room temperature from 25 deg. varies from −0.164 per cent to −0.696 per cent.

It may be well to add that we also tested the open 7½-h.p.

motor with the entire frame covered with asbestos lagging, in order to eliminate radiation losses, as far as possible, and the results were not sufficiently different from the open motor without the asbestos lagging, to warrant our including them in this paper.

B. 20-h.p., 700-rev. per min., 230-volt, 75-ampere motor with fan.

1. Open motor. (See Fig. 10.) Run at rated load until conditions were constant. One run at 25.5 deg.; one at 29; and two at 41.5 deg. All parts except armature core and commutating spool show lower rise at hot room temperature.

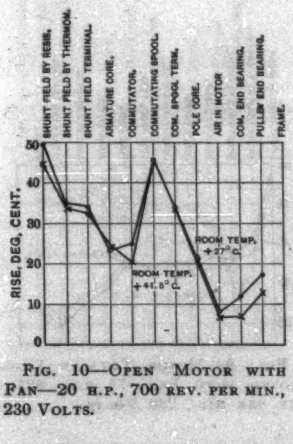


FIG. 10—OPEN MOTOR WITH FAN—20 H.P., 700 REV. PER MIN., 230 VOLTS.

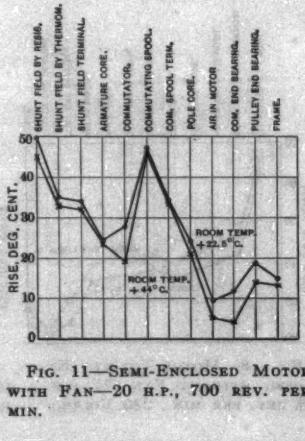


FIG. 11—SEMI-ENCLOSED MOTOR WITH FAN—20 H.P., 700 REV. PER MIN.

Correction to be applied to rise per degree difference of room temperature from 25 deg. varies from -0.152 per cent to -1.25 per cent, for all parts except those mentioned.

2. Semi-enclosed. (See Fig. 11.) Run at rated load until conditions were constant. One run at 21 deg.; one at 24 and two at 44. All parts, except armature core and commutating spool, show less rise at the hot room temperature.

Correction to be applied to rise per degree difference of room temperature from 25 deg., varies from -0.314 per cent to -3.19 per cent.

3. Totally enclosed motor. (See Fig. 12.) Run at one-half

rated load until conditions were constant. One run at 18 deg.; one at 20 deg.; one at 43 and one at 42.

All parts show lower rise at hot room temperature.

Correction to be applied to rise per degree difference of room temperature from 25 deg. varies from − 0.108 per cent to − 0.916 per cent.

Commercial Tests. In the case of these tests, the data on a great many machines of like rating and condition of heat run, were examined, and as a first step the rises of the different parts were plotted against the room temperatures. Examples of this

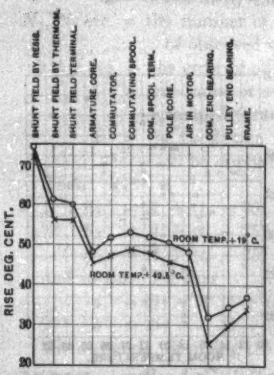


FIG. 12—TOTALLY ENCLOSED MOTOR WITH FAN—20 H.P., 700 REV. PER MIN.

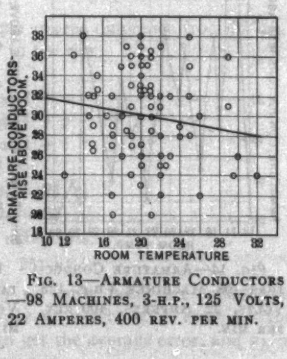


FIG. 13—ARMATURE CONDUCTORS —98 MACHINES, 3-H.P., 125 VOLTS, 22 AMPERES, 400 REV. PER MIN.

may be found in Figs. 13 and 15 if we disregard the straight line. The procedure of analyzing the results is as follows:

We have given certain observed values of temperature rise in degrees cent. on different parts of electrical machines of the same type, rating and duration of run, at different room temperatures given in degrees cent.

Considering any one part, the second step taken was to obtain an average of the observed values of rise at each of the different observed values of room temperature. This will then give us a single value of rise for each room temperature, which, when considered with the total number of observations used to get

this average, will be equivalent to all the observed values of rise, at any one room temperature, considered individually. An example of this is given in Fig. 14, where any one point represents the average of the number of observations used to determine that point.

We then proceeded by making the following assumptions:

1. That there is a true value of temperature rise based on a standard room temperature of 25 deg.

2. That a change of temperature rise, due to a different room temperature, is proportional to a certain percentage of the difference between that room temperature and 25 deg.

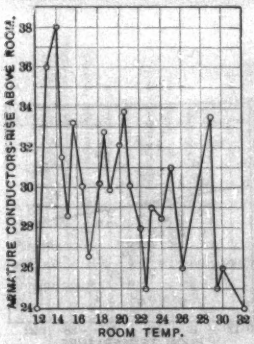


FIG. 14—ARMATURE CONDUCTORS—98 MACHINES, 3-H.P., 125 VOLTS, 22 AMPERES, 400 REV. PER MIN.

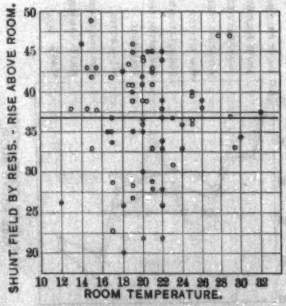


FIG. 15—SHUNT FIELD BY RESISTANCE—89 MACHINES, 3-H.P., 125 VOLTS, 22 AMPERES, 400 REV. PER MIN.

3. That the actual temperature rise at any room temperature is equal to the true rise at 25 deg. plus a certain percentage of that rise, based on the differences of actual room temperature from 25 deg. plus an error of observation, or accidental variation of test conditions.

4. That each value has a weight corresponding to the number of observations.

5. That the algebraic sum of all the errors is equal to zero.

6. That, from mechanical analogy, each average of observed values, multiplied by the number of observations giving that average, and again multiplied by its distance from the line (*i.e.*

its error) is a force pulling the line toward itself; the lever arm of said force being equal to the observed room temperature minus 25 deg. cent., and that the line which we are seeking to represent the mean of observed values of temperature rise at different room temperatures, is in equilibrium when all the moments of these forces, obtained by multiplying them into said lever arm, are jointly equal to zero.

Then, let

t_1, t_2 etc. = the observed values of room temperature.

B_1, B_2 etc. = the average of observed values of temperature rise at t_1, t_2, etc.

N_1, N_2 etc. = the number of observations for any one average of observed values.

a, b, c etc. = the error of observation of B_1, B_2, etc.

A = true value or average rise, based on 25 deg. room temperature.

x = the correction per degree difference from 25 deg. to be applied to the rise.

Then

$$B_1 = A + (t_1 - 25)\, x\, A + a$$
$$B_2 = A + (t_2 - 25)\, x\, A + b$$
$$B_3 = A + (t_3 - 25)\, x\, A + c$$

and so on. Further

$$a = B_1 - A\,\{1 + (t_1 - 25)\, x\}$$
$$b = B_2 - A\,\{1 + (t_2 - 25)\, x\}$$

Or in general, dropping the subscripts,

an error $= B - A\,\{1 + (t - 25)\, x\}$

Referring to assumption 5, we must take care, under our system of averages, to multiply or weight each error by the number of observations used to get the average error, and so, in accordance with the said assumption,

$$\Sigma\, N\,[\,B - A\,\{1 + (t - 25)\, x\}\,] = 0$$

In accordance with assumption 6, we then have

$$\Sigma\, N\,[\,B - A\,\{1 + (t - 25 \text{ deg.})\, x\}]\,(t - 25) = 0$$

We then have two simultaneous equations in A and x, and hence can solve for these constants and obtain the desired line.

After using the above method we discovered an application of the method of least squares given by Weisbach in *Mechanics of Engineering*, pages 95 to 98, applicable to this problem. We have proved to our satisfaction that our method and the method of least squares, as quoted above, are identical.

In accordance with this procedure, we have then added to Figs. 13 and 15 the lines which represent the mean of observed values of temperature rise at different room temperatures.

In the following, the rating and conditions under which the heat run was made, the number of machines tested under similar conditions, and the variation of room temperature will be given. Also the variation of the correction to be applied, based on the rises for the main parts, will be recorded. The parts on the direct-current machines, whose rises were reduced to a mean slope, and corrections calculated, are:

Shunt field by resistance.
Shunt field by thermometer.
Armature core.
Commutator.

On the alternating-current machines:

Armature conductors by thermometer.
Armature conductors by resistance.
Armature core.
Pole core.

In the one case, where induction motors were investigated, only rises on the stator conductors by resistance and by thermometer were reduced to a mean slope.

A. 3-h.p., 125-volt, 400/535-rev. per min. direct-current totally enclosed motors with a two-hr. heat run at normal load.

1. Run at 535 rev. per min. All parts to which our method was applied show a negative slope, varying from − 0.959 per cent to − 2.75 per cent.

The above values are based on 79 machines, with the room temperature varying from 13 to 26 deg.

2. Run at 400 rev. per min. All slopes negative, varying from − 0.014 per cent to − 0.481 per cent.

The above values are based on 89 machines, with the room temperature varying from 12 to 32 deg.

B. 22-h.p., 650/1050-rev. per min., 120-volt, direct-current, semi-enclosed motors.

The runs were made until constant. There were 28 machines, with the room temperature varying from 23 to 34 deg. The rises of the shunt field and commutator gave a slope of from − 0.601 per cent to − 0.661 per cent, while the armature core gave a slope of + 0.094 per cent.

C. Direct-current, open motors; run under normal load until constant.

1. 20-h.p., 1100-rev. per min., 220-volt motors. Here we found 57 machines with the room temperature varying from 15 to 34 deg., which gave corrections for shunt field of − 0.066 per cent by resistance, and − 0.382 per cent by thermometer, while the armature core gave + 0.302 per cent and the commutator + 1.2 per cent.

2. 35-h.p., 600-rev. per min., 220-volt motors. Runs were obtained from 41 machines, with room temperature varying from 13 to 32 deg. Here the shunt field by resistance gave a correction of + 1.04 per cent; while the shunt field by thermometer gave − 1.84 per cent; the armature core − 2.03 per cent and the commutator + 0.118 per cent.

3. 60-h.p., 550-rev. per min., 220-volt motors. Twenty-five machines with a variation of room temperature from 12 to 31 deg., gave a correction for the shunt field and armature core of from − 0.241 to − 2.171 per cent; while the commutator gave + 0.993 per cent.

D. Single-phase, alternating-current generators. Run under normal load until constant.

1. 90-kw., 900-rev. per min., 60-cycle, 2300-volt form "B" generators. Thirty-nine machines, with room temperature varying from 18 to 29, gave all negative corrections, varying from − 0.055 per cent to − 1.46 per cent.

2. 90-kw., 900-rev. per min., 60-cycle, 2300-volt form "A" generators. Thirty-nine machines, with room temperature varying from 18 to 29 deg., gave corrections varying from − 0.032 per cent to − 2.178 per cent.

3. 120-kw., 900-rev. per min., 60-cycle, 2300-volt generators. Under this rating we found 41 machines with room temperature varying from 16 to 35 deg. All parts, except armature conductor by resistance, gave a negative correction varying from − 0.87 per cent to − 1.224 per cent; while the armature conductors by resistance gave + 0.607 per cent.

4. 120-kw., 1070-rev. per min., 125-cycle, 2300-volt generators. Thirty machines, with room temperature varying from 15 to 33 deg., gave corrections varying from − 0.7 per cent to − 2.47 per cent.

E. 1-h.p., 1800-rev. per min., 60-cycle, 110-220-volt, induction motors. Run under normal load until constant.

In the case of induction motors we have but two values of slope; one for the stator conductors, by thermometer, of − 1.21 per cent, and the other for stator conductors, by resistance, of

— 0.56 per cent. This is based on 33 machines, with a room temperature varying from 13 to 30 deg.

F. 150-h.p., 400/600-rev. per min., 220-volt, direct-current motors.

Tests on these machines are very recent ones; in fact, they have not as yet been completed, and we include them because of the marked difference in the runs at different room tempera-

TABLE I

VALUES OF CORRECTION IN PER CENT
SPECIAL TESTS

Part	7½-h.p. motor				20-h.p. motor—W. F.		
	O. No F.	S. E. W. F.	T. E. No F.	T. E. W. F.	T. E.	S. E.	O.
Shunt field by resistance	—0.193	—0.318	—0.233	—0.244	—0.108	—0.417	—0.64
Shunt field by thermometer	—0.333	—0.678	—0.477	—0.364	—0.375	—0.314	—0.244
Shunt field terminal	—0.412	—0.495	—0.443	—0.164	—0.328		—0.291
Armature core	—0.272	—0.310	—0.465	—0.226	—0.248		
Commutating spool	—0.215	—0.392	—0.305	—0.416	—0.345		
Commutating spool terminal	—0.249	—0.502	—0.350	—0.366	—0.332		
Commutator	*	—0.570	—0.384	—0.366	—0.238	—1.35	—1.25
Pole core	—0.103	—0.216	—0.495	—0.209	—0.427	—0.577	—0.341
Commutator end bearing	—0.754	—1.36	—0.785	—0.334	—0.916	—3.19	—2.75
Pulley end bearing	—0.716	—1.32	—0.282	—0.696	—0.536	—1.23	—0.152
Frame	—0.410	—0.72	—0.514	—0.239	—0.300	—0.761	—0.283
Number of tests	4	4	4	4	4	4	4
Range of room temperature in deg. cent	23 to 45	25 to 47	21 to 45	25 to 45	18 to 43	21 to 44	25 to 42

* Corrections not calculated because data were considered incorrect due to rough commutator. Other blank spaces indicate that on these parts the data pointed in no definite direction and it was not considered advisable to apply the least square method to so small a number of tests.

tures. There are only eight runs on four different machines, run at normal load (400 rev. per min.) for eight hours, and we do not consider these tests in the class of accurate ones. The room temperature varied from 21 to 39 deg. The corrections varied from — 0.278 per cent to — 2.78 per cent.

A general summary of the corrections found, is given in Tables I and II. An explanation of the abbreviations used will probably be necessary.

O is used to represent open motor.
S.E. " " " " semi-enclosed motor.
T.E. " " " " totally enclosed motor.
No F. " " " " motor without fan.
W.F. " " " " motor with fan.

TABLE II
VALUES OF CORRECTION IN PER CENT
COMMERCIAL TESTS

Part	3 h.p. T. E.		22 h.p. S. E.	20 h.p. O.	35 h.p. O.	60 h.p. O.	150 h.p. O.
	400 r.p.m.	535 r.p.m.	650 r.p.m.	1100 r.p.m.	600 r.p.m.	550 r.p.m.	400 r.p.m.
Shunt field by resistance	−0.014	−2.75	*	−0.066	+1.04	−2.17	−2.78
Shunt field by thermometer	−0.264	−1.03	−0.661	−0.382	−1.84	−1.24	−0.278
Armature core	−0.187	−0.959	+0.094	+0.302	−2.03	−0.241	−0.212
Commutator	−0.481	−1.09	−0.601	+1.20	+0.118	+0.993	
Number of tests	89	79	28	57	41	25	8
Range of room temperature	12 to 32	13 to 26	23 to 34	15 to 34	13 to *32	12 to 31	21 to 39

Part	Alternators				Ind. Motor
	90 kw. O-B	90 kw. O-A	120 kw. O-A	120 kw. O-A	1 h.p. O
	900 r.p.m.	900 r.p.m.	900 r.p.m.	1070 r.p.m.	1800 r.p.m.
Armature conductors (by res.)	−0.055	−2.178	+0.607	−0.700	
Armature conductors (by ther.)	−1.46	−0.032	−1.224	−2.44	
Armature core	−1.35	−0.991	−1.09	−2.46	
Pole core	−1.00	−0.407	−0.870	−2.47	
Stator conductors (by res.)					−0.557
Stator conductors (by ther.)					−1.21
Number of tests	39	39	41	30	33
Range of room temperature	18 to 29	18 to 29	16 to 35	15 to 33	13 to 30

* Data not reliable. Other blank spaces indicate that such parts are not found on the particular machines or that such parts were not investigated.

In these tables we have given the different parts with the value of correction found for each part for each type of motor, the number of tests, and the range of room temperature.

We have not included in this table the results on the 7½-h.p.

open motor with fan and semi-enclosed motor without fan, results of which, we have said before, showed great inconsistency, and since there were only a few tests, we did not consider it advisable to apply the method used to determine the line of mean slope, that was used in the case of the large number of commercial tests.

Tables I and II represent a total of 2211 values of observed temperature rise on the various types of machines. Of this number 1921 show a negative correction, while 290 show a positive. In other words, about 86.9 per cent indicate that the temperature rise on motors and generators is less in a hot room than in a cold one, while 13.1 per cent indicate the opposite.

The average of all these values of correction is − 0.7 per cent.

In these tests no account has been taken of the temperature of the walls of the room as compared with the temperature of the air. In hot weather the temperature of the walls might be about the same as that of the surrounding air, but in cold weather the walls of a heated room would be of lower temperature than the surrounding air and might affect the direct radiation of the motor to some extent. This matter will be investigated later.

It should be noted that the field rise as determined by resistance falls less with increased room temperature than the reduction of heat dissipated; *i.e.*, if the energy dissipated by the field coil was maintained constant, the field coils would probably show a higher rise of temperature in a hot room. This condition is expected to exist in case of generators.

Conclusions

We believe that the information submitted warrants us in drawing the following conclusions:

1. The present correction rule is wrong and should be abrogated.

2. The considerable variations obtained show the difficulty of making a rule that will include all types of machines or even all parts of the same machine.

3. A consideration of the total temperature obtained when working under normal conditions in the maximum room temperature, is of more importance than the rise of temperature.

4. Further tests leading to a determination of a correct rule, if possible, are desirable.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

EFFECT OF AIR TEMPERATURE, BAROMETRIC PRESSURE AND HUMIDITY ON THE TEMPERATURE RISE OF ELECTRIC APPARATUS

BY C. E. SKINNER, L. W. CHUBB AND PHILLIPS THOMAS

Heat is dissipated from any given piece of electrical apparatus through conduction, convection and radiation. The proportion dissipated through conduction and radiation is usually quite small, although heat is readily conducted from one part of a machine or apparatus to other parts and to supports in contact. The heat dissipated by convection, as a rule, takes care of the major part of the loss.

The present Standardization Rules of the Institute, under the heading of "Temperature Correction" (Section 269), read as follows: "If the room temperature during the test differs from 25 deg. cent., correction on account of difference in resistance should be made by changing the observed rise of temperature by one-half per cent for each degree centigrade." This correction is required, apparently, on the assumption that the increase in resistance of the copper windings is the controlling feature causing such variation.

The factors which affect the variation in temperature rise in a piece of electrical apparatus include the following:

First: Variation in resistance with temperature. The resistance of the copper increases with temperature and the correction for copper loss should be plus or minus, depending on whether the current in a given winding is constant or whether the voltage across the winding is constant.

Second: Variation in iron loss with temperature. Other con-

ditions being constant, iron loss decreases as temperature increases, due

a. To increased resistance reducing eddy-current losses.

b. Decreasing hysteresis losses.

Third: Variation in amount of heat radiated at different temperatures. Under ordinary conditions the amount of heat radiated will vary with the increase in difference between the temperature of the body from which heat is radiated and the temperature of the surrounding objects. The effect of radiation on temperature rise will depend on surrounding conditions, but as a rule there will be more heat radiated from higher temperatures than from lower temperatures.

Fourth: Variation in convection due to variation of viscosity of the cooling medium. There is probably not sufficient variation in the viscosity of air to warrant any correction whatever for viscosity in air-cooled apparatus. This feature becomes quite a factor in oil-cooled apparatus, where the fluidity of the cooling medium increases with temperature, and consequently, its ability to carry away heat by increased rapidity of circulation.

Fifth: Variation due to change in thermal conductivity of the air at different temperatures.

Sixth: Variation due to barometric pressure. It is to be expected that with decreased barometric pressure there will be increased temperature rise, and the results of a given set of tests under specific conditions, recorded later, indicate an increasing rise with decreased pressure.

Seventh: Variation due to humidity. It has been assumed that on account of the heat-carrying power of water vapor there should be a decreased rise due to increased humidity. This corrective factor is, however, probably very small.

Eighth: Variation in bearing friction, brush friction and windage.

Ninth: Variation depending on whether the apparatus is acting as a motor or generator at constant voltage, or whether it is operating at constant load, constant current or constant loss. Whether the total losses on a given piece of apparatus increase or decrease with temperature, depends on how the apparatus is operated and on the relation of the various segregated losses to each other. If operating as a generator with constant output the copper losses will increase with rise in air temperature and the iron losses may increase or decrease. If the iron loss pre-

dominates, the result may be a decrease in actual losses with increase in air temperature, giving a lower rise. If operating as a motor or transformer and connected to a constant voltage, increased air temperature may again either increase or decrease the total losses, and the rise, as in the case of a generator.

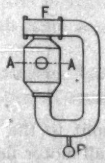
A number of tests indicating that the correction for temperature rise when the air temperature is higher than 25 deg. cent. should be negative instead of positive, as required by the Standardization Rules, has led to a set of tests being made to determine some of the fundamentals which govern temperature rise from different temperatures. It will readily be seen from the foregoing that the problem is an extremely complicated one and that it is necessary, therefore, to fix certain conditions and provide for the observing of one variable at a time, keeping the others constant if possible. The factors which were controlled in these tests were:

a. Radiation
b. Air temperature.
c. Barometric pressure.
d. Humidity.
e. Wind velocity.
f. Input.

All tests were made with a constant input to the test coil.

The apparatus selected for test was a small motor field coil, of about 9 ohms resistance at 20 deg. cent. The coil was about 6.35 cm. (2.5 in.) by 1.9 cm. (0.75 in.) in section, and was wound on a center block about 9 cm. (3.5 in.) by 5 cm. (2 in.). The block was removed before setting up for the tests. This coil was hung in the center of a closed cubical box, about 61 cm. (2 ft.) on a side. At two opposite ends of the box, connection was made with an air circulating pipe 30.5 cm. (1 ft.) in diameter, which formed a closed system with the box and a blower. The whole system was made as nearly air-tight as possible, and variation in internal pressure was secured by means of a motor-driven air pump used either to exhaust or compress the air in the system. A cubical sheet metal baffle was mounted inside the coil box, equipped with a fine mesh screen at the ends through which the air entered and left the coil space. About two inches (51 mm.) of free air space was left on all sides between the baffle and the coil box, in order to be sure that the temperature of the baffle wall and the air surrounding the coil should be the same. The screen across the ends of the baffle also extended across the clearance to the inside of the coil box. The pressure within the

system was read on a differential mercury manometer communicating with the atmosphere outside; the external pressure was given by a carefully adjusted aneroid barometer. The velocity of the circulating air was measured by the cooling effect upon a small copper wire suspended directly beneath the coil, the air speed being calculated from the current necessary to maintain the resistance of this wire, between definite potential points, at a predetermined constant value.* The temperature of the coil, and of the air directly above and below the coil, was given by iron-advance thermocouples. The coil couple was mounted in contact with the covering of the wire on the extreme upper surface of the coil, which was subsequently given a serving of cotton tape and two coats of black armature varnish and



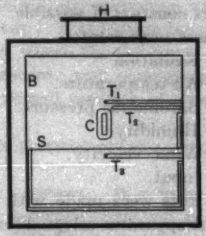


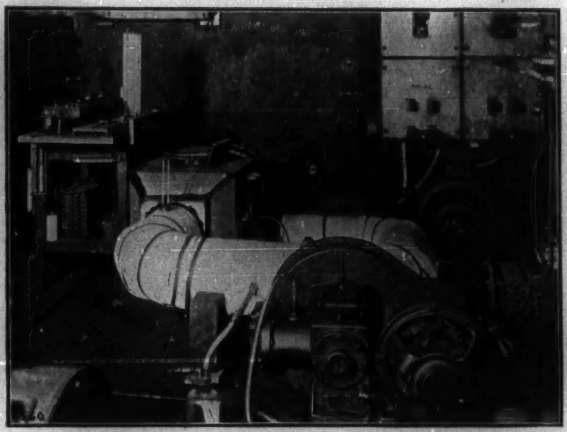
FIG. 1A—TOP VIEW OF APPARATUS. FIG. 1B—SECTION A-A, SCHEMATIC

F — Blower.
P — Air pump.

C — Coil tested.
S — Speed wire.
T_1, T_2, T_3 — Thermocouples.
B — Air baffle.
H — Handhole for making adjustments.
Direction of flow of air is at right angles to plane of section.

baked dry. The relative humidity of the circulating air was determined from the readings of a wet and dry bulb thermometer, with the bulbs in the path of the air just before entering the coil enclosure. The temperature of the circulating air could be varied within wide limits by electric heater elements inserted in the air-pipe just after leaving the coil box, so that the heated and cooler air would be thoroughly mixed before again entering the enclosure. Fig. 1, schematic, shows the location of the coil, velocity wire and thermocouples, the leads from all of which were brought out through rubber corks in the sheet-iron covering of the coil box.

*Kennelly, Wright and Van Bylevelt, TRANSACTIONS A. I. E. E., 1909, XXVIII, I, p. 363.



[SKINNER, CHUBB AND THOMAS]

SHOWING APPARATUS USED IN MAKING TESTS.

The temperature elevation of an air-cooled coil is apparently influenced by so large a number of factors, that the futility of an attempt to determine the effect of each of them, in the time available, was apparent at the outset. The most important of the controlling factors are the temperature and pressure of the surrounding air. The major part of the work was then concentrated upon determinations of the effects of these two factors. Two sets of runs were made: First, with constant watts input in the tested coil, and constant pressure and speed of the circulating air, the temperature in the enclosure was varied by small steps from 30 to 64 deg. cent., and the temperature of the coil was taken at each point. Second, with constant watts input in the tested coil, constant temperature in the enclosure, and constant speed of air circulation, the air pressure in the enclosure was varied from 82.8 cm. (32.6 in.) to 53.4 cm. (21.0 in.) of mercury, in small steps, and the temperature rise of the coil was taken at each point. No readings were finally recorded at any point, until the instrument readings had all been constant for at least half an hour.

The current passed through the test coil was measured by a precision ammeter, and the difference of potential between the terminals of the coil was measured by a precision voltmeter connected to potential leads. Rough tests indicated that the temperature elevation of the coil was about 28 deg. cent. when carrying 32 watts, and the coil current and potential difference were kept such as to maintain this input as nearly constant as possible during the tests. The current through the speed wire was adjusted to give the same temperature elevation as in some previous work which has been presented before the Institute; this current was measured by a low-scale ammeter, and the potential across a length of the wire equal to that used in the same tests, was measured by a potentiometer.

Readings of the wet and dry bulb thermometers were made at each point in every test, with the intention of correcting for the slight variations in humidity unavoidably occurring; but a subsequent test, made with the air nearly saturated by blowing steam into the system, showed no significant change in temperature rise, and it was thought inadvisable to attempt any such corrections.

Results

A. Tests at Constant Air Pressure and Speed. Fig. 2 shows in graphic form the results of these tests. Each point required

several hours for its determination, so that the test as here recorded extended over several days. The curve between box temperature and coil temperature, plotted to the same scale, is plainly a straight line, within errors of observation and of adjustment of the controlling factors: the points as obtained do not indicate any regular deviation from a straight line. The intercept value of temperature rise as given by this line agrees closely with the average of the point values, which means that the temperature elevation is constant. It may be mentioned here that the readings on the speed wire, worked out by the

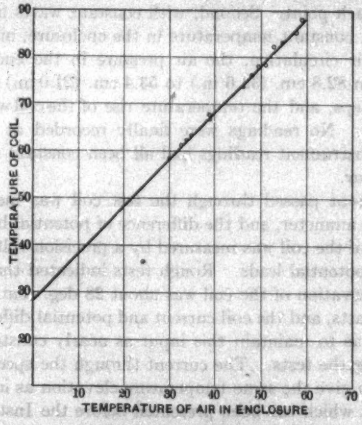


FIG. 2—VARIATION OF TEMPERATURE RISE OF COIL WITH CHANGING TEMPERATURE OF SURROUNDING AIR

equation given for the same size, length and temperature of wire, in the paper already mentioned, gave an air velocity of 146 cm. per sec. (3.27 miles per hour) for a blower speed of 789 rev. per min. This speed was read on a tachometer and was kept very closely constant during the entire test. The temperatures above and below the test coil proved to be identical, when the air was circulated at this speed. Table I gives the observational results from which the curve of Fig. 2 was plotted.

B. Tests at Constant Air Temperature and Speed. The results of these tests are shown in Table II, and graphically in Fig. 3. The column headed "coil input" shows the variations

that occurred in this quantity during the test. In order to correct the temperature rise for this error, a test was subsequently run between watts input and temperature rise, at the same fan speed and box temperature as were employed in the present test, and at constant air pressure. The results showed the relation between coil temperature and coil input to be very nearly linear; the exact equation found was

$$W = K\theta^{1.015}$$

Accordingly a correction for variation in input was made at each point taken; the curve plotted in Fig. 3 is taken from

TABLE I

EFFECT OF VARIATION OF TEMPERATURE OF ENCLOSURE UPON TEMPERATURE RISE OF COIL

Couple temperatures, deg. cent			Coil input, watts	Blower speed rev. per min.
Air in box	Coil	Coil rise		
64	92	28	31.6	787
62.5	90.2	27.7	31.7	789
59.6	88	28.4	31.9	787
58	85.2	27.2	31.7	760
55	83	28	31.7	790
53.2	82.2	29	31.6	789
51	78.5	27.5	32.6	785
49.5	78	28.5	31.2	790
48.5	76.2	27.7	31.9	790
46.1	73.5	27.4	31.9	782
39.2	67	27.8	31.5	776
39.2	66.8	27.6	31.6	781
39	67.5	28.5	31.9	780
35	63.1	28.1	31.8	777
34	62.2	28.2	31.7	783
33	61	28	32	787
30	58.2	28.2	31.7	779

these corrected values. As this curve shows about a 13 per cent variation in temperature rise for a decrease of 15 cm. (5.9 in.) in atmospheric pressure, which corresponds to a change in altitude from sea level to 1.9 km. (6240 ft.) above sea level, the importance of determinations of the magnitude of this effect on finished electrical apparatus is at once apparent. It is possible that some of this increase in temperature rise, as the air pressure is decreased, may be due to changes in the air velocity at different pressures with the same speed; but operating conditions are much more nearly those of constant fan speed than of necessarily constant air velocity.

Summary

The tests which have been completed at the time of writing this paper are:

First: The determination of the rise in temperature, all features being kept constant, except the temperature of the air and the surrounding walls.

Second: The determination of the variation in rise of temperature, all features being kept constant, except the barometric pressure.

Third: Some additional data were obtained showing variation of rise in temperature, all features being kept constant, except humidity of the surrounding air, but no difference in temperature rise due to variation in humidity was found.

Tests are under way to determine the rise in temperature,

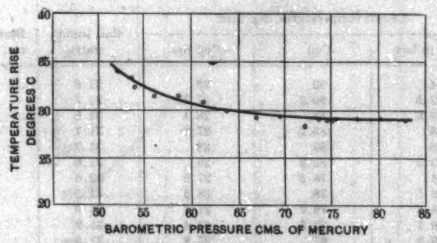


Fig. 3—Variation of Temperature Rise of Coil with Barometric Pressure

keeping all features constant, except the temperature of the surrounding air, with a view to determining the effect of varying radiation.

Results of the first set of tests are shown in Fig. 2. It will be seen that within the limits of error of observation and under the conditions of the test as made, a variation in the temperature of the air surrounding the coil does not affect the temperature rise. The slight difference in the amount of heat radiated from the coil at different temperatures, even though the surrounding walls were kept at air temperature, does not appear in the recorded results and must, therefore, be very small.

Results of the second series of tests are shown in Fig. 3 and indicate that there is a sufficient amount of variation in the temperature rise of electrical apparatus between sea level and an

altitude of five thousand feet, for example, to require a relatively small corrective factor. The data obtained are, however, probably not sufficiently conclusive to warrant making provision at this time for such correction.

The tests so far recorded with variation in humidity have shown no appreciable variation in temperature rise and these results agree with other work which has been done along this line.

A theoretical discussion of the variation in temperature rise due to variation in radiation, would indicate that under certain conditions the temperature rise from higher air temperatures

TABLE II

EFFECT OF PRESSURE VARIATION UPON TEMPERATURE RISE OF COIL

Air pressure		Couple temperatures deg. cent.			Coil input, watts	Blower speed rev. per min.	Corrected coil rise
Cm.	In.	Air in box	Coil	Coil rise			
82.7	32.6	41	69.5	28.5	31.7	785	28.7
80.2	31.6	40.8	69.6	28.8	31.7	786	29
77.6	30.5	40.9	69.7	28.8	31.8	784	29
75.5	29.7	41.8	70.5	28.7	31.8	789	28.9
75.3	29.6	40.9	69.5	28.6	31.8	785	28.8
74.6	29.2	40.2	68.9	28.7	31.8	784	28.9
73.7	29	40	67.8	27.8	31.6	782	29.1
72.3	28.5	40.2	69.0	28.8	31.6	787	28.2
69.6	27.4	40	68.8	28.8	31.7	790	29.1
66.9	26.4	40.7	69.5	28.8	31.7	788	29.1
63.8	25.1	40.7	70.3	29.6	31.7	784	29.9
61.4	24.2	40.5	71.2	30.7	32	786	30.7
58.7	23.1	40.5	73.5	33	33.7	785	31.4
56.2	22.1	40.2	73.1	32.9	33.6	787	31.4
54.1	21.3	40.2	72.5	32.3	31.6	787	32.4
53.8	21.2	40.4	73.5	33.1	31.8	788	33.4

might be less than from lower air temperatures. As the general tendency of the other factors which affect temperature rise from different air temperatures is to oppose the effect of radiation, these corrections will in general tend to cancel each other.

Conclusion

It will be seen from the foregoing discussion that the problem of the variation in temperature rise from different air temperatures is quite complex and that in some cases the same item of loss may tend to increase or decrease the temperature rise, depending on the conditions under which the apparatus is operated. The con-

clusion which can be drawn from the tests made, is that while there are a number of things which would make the temperature rise from one air temperature differ from that of another, these tend to cancel each other and, therefore, the omission of any corrective factor for variation in air temperature would be more nearly in accordance with the facts than the provision made in the existing Standardization Rules.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

A LABORATORY INVESTIGATION OF TEMPERATURE RISE AS A FUNCTION OF ATMOSPHERIC CONDITIONS

BY C. B. BLANCHARD AND C. T. ANDERSON

The following is a report on laboratory tests made to determine the effect of pressure, temperature and humidity of the air surrounding a heat-dissipating body on its rise in temperature above that of the air.

The original purpose of this paper was to investigate the physical laws governing heat dissipation in air and to attempt to apply these laws to the general problem of temperature rise in electrical machinery. But in working up the results of the tests it was found that there was some uncertainty in the derived quantities because of uncertainties regarding the precise effective area of the heat-dissipating body, the nature of its surface, the temperature gradient from its interior to its surface, and, furthermore, the heat losses through the leads through which electric power was supplied to the body and by means of which its temperature was measured.

This uncertainty is considered such that careful physical derivations are not warranted, and yet the results are considered sufficiently definite for all practical purposes to determine the effect of the various atmospheric conditions on temperature rise of stationary self-cooled and oil-cooled apparatus. It is, therefore, the purpose to set forth herein the details of the apparatus and its manipulation and the data and curves expressing the desired relations, and to postpone the generalizations until further tests have been made. A rough outline of the proposed derivations will be given, however, as preliminary to a subsequent paper.

An outline of the general method of the tests will first be given. Then the apparatus, manipulation, results and discussion will be taken up in order.

General Method

The method of the tests was as follows:

A resistance coil was suspended in a steel tank containing air. The coil was supplied with electric power. After constant temperature conditions obtained, measurements of coil temperature, air temperature, tank temperature, air pressure and watts input were taken. The difference between the air temperature and the coil temperature was called the temperature rise. The variations of this rise with air temperature, air pressure and input were determined by holding two of these constant and varying the remaining one. These tests were made with dry air except when the effect of humidity was being investigated. The details of the apparatus used and the method of test are taken up in the following sections.

The Apparatus

The Test Coil. The heat-dissipating body was a coil of 100 ft. (30.48 m.) of insulated copper wire of 0.018 in. (0.457 mm.) diameter with a coat of black enamel of 0.001 in. (0.025 mm.) thickness and one layer of cotton of 0.0025 in. (0.0635 mm.) thickness. Wound turn by turn with this wire was an equal length of copper wire of 0.005 in. (0.127 mm.) diameter with a coat of enamel 0.00025 in. (0.00635 mm.) in thickness. These two wires formed a coil of 5.08 cm. internal diameter, 7.02 cm. external diameter and 0.635 cm. thickness. The leads which were soldered to the ends of these windings were of copper wire of 0.041 in. (1.04 mm.) diam. with 0.0015 in. (0.038 mm.) enamel. The pyrometer leads were 12.7 and 14 cm. in length; those of the other winding were 12.7 and 16.5 cm. in length. The leads were soldered to pieces of double lamp cord of 16 strands of 0.0125 in. (0.3175 mm.) diameter each with a coating of rubber 0.025 in. (0.635 mm.) in thickness and cloth 0.01 in. (0.25 mm.) in thickness, and 120 cm. in length. The soldered joints at the coil were taped and tied to the coil. The whole coil was wrapped transversely with 140 cm. of hemp string of about one mm. thickness to insure mechanical strength. The coil was then soaked in japan and baked. The soldered joints at the lamp cord were left untaped. These details are given for the benefit of any one who cares to investigate the results of these tests.

The Air Tank. The air tank is shown diagramatically in Fig. 1. It is of cylindrical form, 68 cm. in diameter and 68 cm. in depth. It has a flange at the upper edge to which the cover can be bolted. Pipe connections are made through one side for pressure control. The cover contains two fiber plugs through which the electrical terminals pass. The whole vessel is painted black inside. This tank is supported inside a second tank of 100 cm. diameter and 100 cm. depth, containing oil. Beneath the air tank is an electrical heating element of about two kw. capacity for controlling the temperature.

The Pyrometers. The test coil pyrometer has already been described. The air pyrometer consists of three coils of 0.003-in. (0.076 mm.) cotton-covered wire wound on fiber frames so that

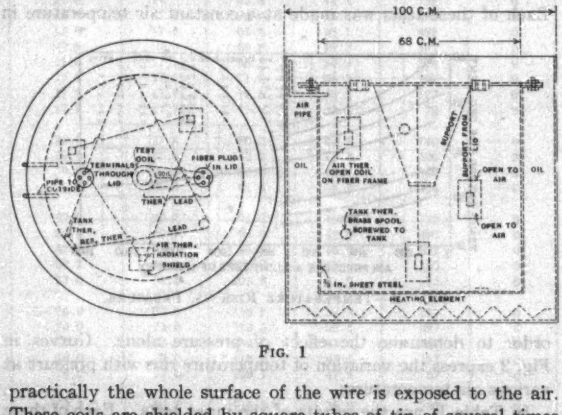


FIG. 1

practically the whole surface of the wire is exposed to the air. These coils are shielded by square tubes of tin of several times the diameter of the coil. They are open at both ends, allowing free passage of air over the coils, at the same time shielding them from any direct radiation from the test coil. These coils are connected in series. The total resistance of this pyrometer is about 110 ohms. The tank pyrometer consists of three brass spools wound with 0.003-in. (0.076 mm.) cotton-covered wire. These spools are screwed to the tank at various points. The coils are connected in series. The total resistance of this pyrometer is about 100 ohms.

Each pyrometer is connected through leads in the fiber plugs to the outside of the tank.

The Set-Up. The air tank then consisted of a test coil suspended in the center of the air tank by twin strings, and loaded by a storage battery through terminals in the cover. The power was varied by a rheostat and read by a direct potential voltmeter and ammeter.

The temperatures were read by measuring the resistances of the pyrometers with a portable bridge. The coils were very carefully calibrated and the temperatures were read from curves.

The air pressure in the tank was controlled by connections with compressed air and vacuum lines. It was measured by means of a mercury column.

Manipulation

In Tables I and II are the results of the constant input tests. Each of these tests was made at a constant air temperature in

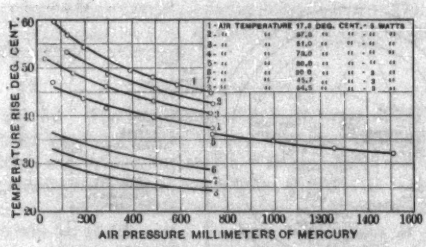


Fig. 2—Temperature Rise vs. Pressure.

order to determine the effect of pressure alone. Curves in Fig. 2 express the variation of temperature rise with pressure at various air temperatures.

In Table II are the results of the input tests. Each of these tests was made holding air pressure and air temperature constant and varying the watts input. The curves in Figs. 4, 5 and 6 express the variation of temperature rise with watts input at various air pressures and temperatures.

The tests so far outlined were made with dry air. The air before entering the tank was caused to pass through sulphuric acid, calcium chlorid and phosphorus pentoxid.

The last two items in Table I are the results of the humidity tests. In these tests the air was passed through an electric oven which contained a large wetted surface. Great care was taken

to pass the air from the humidifier to the test tank without condensation.

Results

The data curves of Fig. 2 express the variation of temperature rise with pressure. The second set of curves on this figure was

TABLE I

VARIATION OF TEMPERATURE RISE WITH AIR TEMPERATURE, PRESSURE AND HUMIDITY.

Tank temp.	Air temp.	Coil temp.	Temp. rise	Pressure mm.	Humidity per cent saturation
deg. cent.	deg. cent.	deg. cent.	deg. cent.		
17.5	18	62.8	44.8	732	0
17.8	17.5	64.0	46.5	592	0
17.8	17.5	65.6	48.1	492	0
17.8	17.5	66.8	49.3	392	0
17.5	17.4	68.3	50.9	294	0
17.8	17.5	71.8	54.3	197	0
17.8	17.7	74.5	56.8	127	0
17.8	17.7	77.5	59.8	72	0
39.0	37.8	80.3	42.5	740	0
39.0	37.5	83.2	45.7	500	0
39.2	37.8	86.5	48.7	300	0
39.5	38.0	91.4	53.4	125	0
52.2	50.7	91.2	40.5	732	0
52.5	50.7	93.5	42.8	492	0
52.5	50.5	96.5	46.0	292	0
52.7	51.0	100.0	49.0	152	0
53.0	51.5	103.3	51.8	32	0
76.2	73.5	110.8	37.3	737	0
76.0	73.0	112.5	39.5	497	0
76.0	73.0	114.6	41.6	297	0
76.0	73.0	116.5	43.5	197	0
76.0	73.0	120.1	47.1	67	0
82.5	80.2	116.25	36.0	737	0
82.2	80.0	114.75	34.8	995	0
82.0	79.7	112.9	33.2	1254	0
83.0	80.2	112.3	32.1	1512	0
18.8	19.5	64.4	44.9	732	71
38.5	38.5	81.1	42.6	741	95

derived from the input curves of Figs. 4, 5 and 6 by drawing ordinates at three watts and plotting the intersections with the input curves. It will be seen from the curves on Fig. 2 that at normal air pressures there is a variation of temperature rise with pressure of about 1 deg. per 100 mm. Assuming that from

TABLE II
VARIATION OF TEMPERATURE RISE WITH WATTS INPUT, TEMPERATURE AND PRESSURE

Tank temp.	Air. temp.	Coil temp.	Temp. rise	Pressure mm.	Watts input Total
deg. cent.	deg. cent.	deg. cent.	deg. cent.		
19.3	19.6	30.6	11.0	297	0.892
19.4	19.7	41.5	21.8	297	1.911
19.4	19.9	57.3	37.4	297	3.53
19.4	20.0	73.0	53.0	297	5.27
19.6	20.0	82.5	62.5	97	5.587
19.6	20.1	68.2	48.1	97	4.107
19.6	20.0	49.0	29.0	97	2.29
19.6	20.0	37.8	17.8	97	1.318
66.5	63.8	77.1	13.3	727	1.558
66.5	63.8	78.0	12.2	487	1.560
66.5	63.8	78.8	15.0	287	1.56
66.6	64.0	79.7	15.7	147	1.563
66.5	64.4	80.9	16.5	57	1.564
66.7	64.4	81.3	16.9	17	1.564
67.0	64.5	92.2	27.7	727	3.428
66.7	64.8	116.7	51.9	14	5.121
66.5	64.4	120.9	56.5	54	5.910
66.3	63.9	117.7	53.8	144	5.915
66.6	64.2	114.8	50.6	284	5.961
66.6	64.4	112.0	47.6	484	5.941
66.6	64.4	98.4	34.0	484	4.045
46.7	44.8	59.8	15.0	744	1.626
46.7	45.1	73.8	28.7	744	3.33
47.1	45.3	99.7	54.4	744	6.837
47.3	45.5	74.4	28.8	504	3.094
47.5	45.7	76.3	30.4	304	3.078
47.5	46.6	79.5	32.4	104	3.082
47.7	46.6	108.7	61.6	104	6.205
18.7	19.1	22.8	3.9	737	0.34
18.8	19.1	32.9	14.0	737	1.34
18.8	19.3	46.1	26.9	737	2.80
19.4	19.5	69.5	50.1	737	5.73
19.2	19.4	72.7	53.4	497	5.67
19.3	19.6	58.4	39.9	497	3.95
19.3	19.6	40.3	20.8	497	1.92
19.4	19.7	29.9	10.3	497	0.895
67	64.4	83.2	18.8	724	2.287
67	64.4	84.2	19.8	484	2.272
67	64.5	85.5	21.0	284	2.262
67	64.5	86.8	22.3	144	2.252
67	64.7	88.3	23.6	54	2.246
67	64.7	89.7	25.0	14	2.237

three to five watts input for 80 sq. cm., or from 0.0375 to 0.0625 watts per sq. cm., is a practical range of input, this variation seems to be about what would be expected in stationary apparatus.

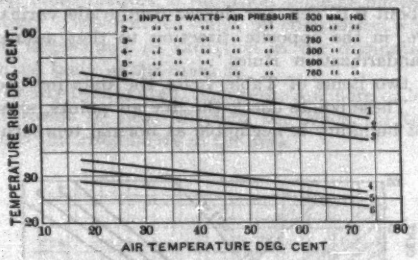


FIG. 3—TEMPERATURE RISE VS. AIR TEMPERATURE.

According to the Standardization Rules, we have, for a variation of 100 mm. from 760,

$$\frac{860-760}{10} = 10 \text{ per cent correction.}$$

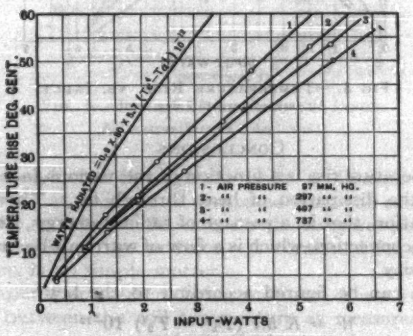


FIG 4.—TEMPERATURE RISE VS. INPUT.
Air temperature 20 deg. cent.

Assuming a temperature rise of 40 deg. cent., we have 40 + 4 = 44 deg. rise. This correction is four times as large as the results of this test would indicate.

The curves of Fig. 3 are derived from curves of Figs. 2, 4, 5 and 6. They express the variation of temperature rise with air temperature. These curves represent the same range of input as do the pressure curves. The variation according to these curves is about 0.15 deg. per degree centigrade variation of air temperature, in the opposite direction to that assumed in the present Standardization Rules.

The last two items of Table I are the data for the effect of humidity. These points check the dry air points, showing that the effect of humidity is negligible at normal temperatures and pressures.

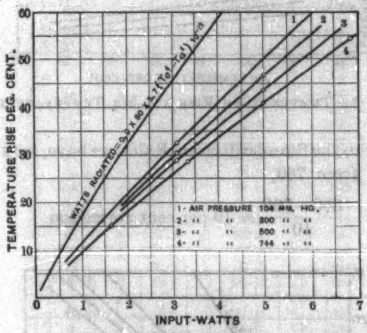


FIG 5.—TEMPERATURE RISE VS. INPUT.
Air temperature 45.7 deg. cent.

CONCLUSIONS

The temperature rise is a function of the various factors which enter into the dissipation of heat through air. These factors are (1) radiation, that is, a passage of radiant energy, (2) conduction and (3) convection, which is a flow of warm air because of decreased density.

Radiation can be figured according to the law

$$W = K\,5.7\,(T_1^4 - T_2^4)\,10^{-12}$$

where K is unity for a black body and less for any other, depending upon the nature of the heated surface. Assuming 0.9 for K for the test coil and putting

$T_1 = Tc$, the test coil temp. absolute,
$T_2 = Ta$, the air temp. absolute,

and taking the effective radiating area as 80 sq. cm., the watts radiated at various air temperatures and temperature rises * were calculated and plotted in Figs. 4, 5, and 6. These curves express temperature rise as a function of watts input at various surrounding temperatures, if radiation alone be allowed to dissipate the heat. These curves show, by comparison with the data curves, the importance of radiation in the dissipation of heat from a heated body in the open air.

As has already been stated, the results are more or less in error because of losses of heat through the leads, the temperature gradient, and the irregularity in the area.

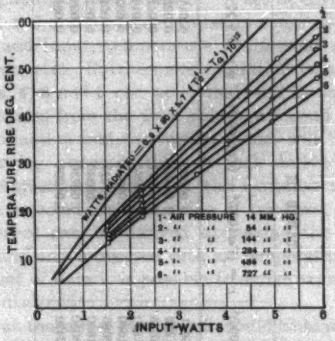


FIG. 6—TEMPERATURE RISE VS. INPUT.
Air temperature 64.5 deg. cent.

Heat is conducted through the leads a distance depending upon the rate at which it is dissipated from the surface of the leads, which, of course, depends on the temperatures and the nature and area of the surfaces. A correction for this loss, as can be seen, is no simple matter.

The temperature gradient being unknown causes an unknown difference between the coil temperature as measured, and the surface temperature upon which the heat dissipation depends.

Whereas these difficulties forbid derivation of physical laws, they are slight from the engineering standpoint. A set of results which are free from these errors is very desirable, however,

*See Table III.

TABLE III

T_a deg. cent.	T_a deg. K	$(T_a/1000)^4$	T_c deg. cent.	T_c deg. K	$(T_c/1000)^4$	$r = (T_c/1000)^4 - (T_a/1000)^4$	$w = 0.9 \times 5.7 \times r$	$W = 80\,w$	$T_c - T_a = T_r$
20	293	0.00738	40	313	0.00961	0.00223	0.01144	0.914	20
20	293	0.00738	60	333	0.01232	0.00494	0.02530	2.026	40
20	293	0.00738	80	353	0.01555	0.00817	0.04200	3.356	60
45.7	318.7	0.01035	65.7	338.7	0.01320	0.00285	0.01460	1.170	20
45.7	318.7	0.01035	85.7	358.7	0.01660	0.00625	0.0321	2.565	40
45.7	318.7	0.01035	105.7	378.7	0.02060	0.01025	0.0526	4.208	60
64.4	337.4	0.013	84.4	357.4	0.01640	0.00340	0.0174	1.40	20
64.4	337.4	0.013	104.4	377.4	0.02030	0.00730	0.0374	3.00	40
64.4	337.4	0.013	124.4	397.4	0.02499	0.01200	0.0615	4.920	60

since the laws of heat conduction and convection in air at various pressures are not as yet well established. Furthermore, the entire problem of heat dissipation in air is important, because when the laws are known electrical machinery can be so designed as to maintain the most efficient system of natural cooling.

Tests which will make possible a physical investigation of heat dissipation in air are being contemplated. A brief outline will be given of the proposed method of attack.

It is hoped to build such apparatus as to dispense with the temperature gradient, surface and heat difficulties. With this apparatus input tests can be made. A set of curves similar to those of Figs. 4, 5 and 6 will determine pressure relations at any temperature and input, temperature relations at any temperature and input, etc. Furthermore, radiation curves similar to those on Figs. 4, 5 and 6 can be plotted, and by subtracting the radiation abscissas from the total values, a second set of curves, involving conduction and convection alone, will be the result. Also, by drawing abscissas through such derived curves and noting the intersections, curves of the variation of watts conducted and convected, as a function of pressure, can be drawn. Similarly, curves can be derived expressing the variation of watts conducted and convected with air temperature. In short, from such a set of data it is possible to derive expressions of the laws of heat dissipation in air.

Such data as those just mentioned should be taken from a surface for which radiation constants are well known. A further investigation of the effect of the nature of the heat-dissipating surface is important.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

LAWS OF HEAT TRANSMISSION IN ELECTRICAL MACHINERY

BY IRVING LANGMUIR

Even in a simple case of heat transmission, such as a laboratory measurement of heat conductivity, the phenomena involved usually prove to be quite complicated. It is in most cases nearly impossible to separate completely the effects of conduction, radiation and convection, and therefore if quantitative results are to be obtained, it becomes necessary to make an elaborate series of corrections, to eliminate the undesired factors.

In the case of the flow of heat from the interior of a piece of electrical apparatus to the exterior, the problem is necessarily much more complicated than in the simple experiment. Since each of the three factors, conduction, radiation, and convection, are subject to totally different laws, the effect of any change in conditions can, in general, be determined only by considering what part each factor plays in the whole process and how each factor is affected by the new change in the conditions.

Failure to appreciate the necessity of separating each of these factors has rendered the majority of all investigations on heat transmission previous to 1880 almost valueless. Even today a very large number of published results on heat conductivity and surface emissivity are thoroughly unreliable from this cause.

It is surprising to what extent the old unreliable data maintain their place in present day hand-books and text-books. There is probably hardly a field in which so much care is needed in selecting proper sources for information, the literature being full of absolutely contradictory statements. For example, one investigator concludes from his experiments that the total heat loss from small wires, heated to a given temperature, varies

in inverse proportion to the diameter, others state that the variation is directly proportional to the diameter, while still others find it to be independent of the diameter.

If electrical engineers are to consider seriously the question of heat transmission in electrical machinery, they must fully realize the great difference between the three modes of heat transmission and determine, first of all, what part each factor plays in each of the many types of machines.

In the present paper the writer has attempted to present in as clear a manner as possible the fundamental laws of conduction, radiation and convection of heat, and to furnish some experimental data which may seem to be of value to the electrical engineer.

Conduction of Heat

The problem of the conduction of heat through solids was the first subject of mathematical and experimental study in the development of the theory of heat. Fourier and others developed the mathematical theory long before there were any reliable experimental data by which they could test their conclusions.

Fourier considered especially the problem of the rate of heating of a body capable of conducting heat. To solve this problem, he invented special mathematical methods which are now studied under the head of Fourier's Series. Because of the extreme complexity of this subject, mathematical analysis does not promise, for the present, to be of much value to the electrical engineer. We shall therefore limit ourselves to the simpler problem of the steady flow of heat which prevails after sufficient time has elapsed for the temperature through the apparatus to become constant.

For this case of steady heat flow through solids, the general law may be stated

$$W = \frac{A}{l}\mathbf{k}\,(T - T_0) \tag{1}$$

where W = Watts of heat flow.

A = Area of cross-section of path of heat flow.

l = Length of heat path.

$\mathbf{k}$ = Coefficient of heat-conductivity expressed in watts per cm. per deg.

$T - T_0$ = Difference of temperature causing the heat flow.

Heat Conductivity of Solids. The heat conductivity, $\mathbf{k}$, of solid bodies varies greatly for different substances, ranging from 4.2 watts per cm. per deg. cent. for pure silver to 0.0016 for such substances as rubber. The conductivity of finely divided solids,

fibrous materials, powders, etc., is very much less than that of homogeneous solids. The best heat insulators known, such as eider-down, have a conductivity as low as 0.00020 watts per cm. per deg. cent.

Unfortunately, all the materials used for electric insulation are relatively poor heat conductors. Especially when the insulation contains air spaces, as in the case of braided coverings, the conductivity is very low.

In Table I the writer has collected together all of the *reliable* data he has, by careful search, been able to find on the conductivity of such materials as are of interest to the electrical engineer.

TABLE I

Thermal Conductivities and Resistivities of Various Materials.

Materials	Temp. deg. cent.	Conductivity watts per cm. per deg. cent.	Resistivity	References
Metals				
Pure copper	18	3.84	0.260	2
Commercial copper	18	3.50	0.285	2
Pure iron	18	0.67	1.49	2
Steel 1 per cent C	18	0.45	2.22	2
Cast iron	100	0.40		
Transformer steel 4 per cent Si	20–250°	0.32	3.12	1
Brass	*	1.30	0.77	1
German silver 30 per cent Ni	*	0.28	3.6	1
Constantan 60 Cu, 40 Ni	18	0.29	3.5	2
Calorite 65 Ni, 15 Fe 13 Cr. 7 Mn	20–250°	0.16	6.2	1
Mineral Substances				
Graphite		3.57	0.28	11
Marble		0.030	33	3
Slate		0.020	50	3
Glass		0.011	90	4
Quartz glass		0.015	67	10
Porcelain		0.010	100	5
Insulating Materials				
Shellac		0.0025	400	4
Para rubber		0.0016	620	3
Gutta percha		0.0020	500	3
Paraffin		0.0026	390	3
Ebonite		0.0018	550	4
Paper		0.0013	770	3
Asbestos paper		0.0025	400	3
Varnished cotton tape		0.0027	370	6
Varnished cambric		0.0025	400	6
Mica paper		0.0016	630	6
Bakelite and linen tape		0.0027	370	6
Rubber tape		0.0043	230	6
Varnished cloth (empire cloth)		0.0025	400	7
Pressphn (untreated)		0.0017	590	7
Rope paper (untreated)		0.0012	830	7
Rope paper and oil		0.0014	710	7
Rope paper treated with varnish		0.0017	590	7
Fullerboard varnished		0.0014	710	7
Pure mica		0.0036	280	7

TABLE I—*Continued.*

	Apparent density grams per. cu. cm.	Conductivity	Resistivity	References
Insulating Materials				
Built-up mica Micanite (19 per cent shellac)		0.0010	1000	7
Built-up mica Micanite (11 per cent shellac)		0.0012	830	7
Linen tape varnished and baked		0.0015	670	7
Miscellaneous Materials				
Cotton batting, loose	0.21	0.00046	2200	1
" " tightly packed	0.10	0.00030	3400	1
Pure woolen wadding, loose	0.015	0.00049	2040	1
" " " packed slightly	0.054	0.00036	2800	1
Pure woolen wadding, tightly packed	0.192	0.00023	4400	1
Eider down, very loose	0.0022	0.00045	2200	1
" " tightly packed	0.077	0.00025	4100	1
" " " " "	0.11	0.00019	5200	1
Soft white pine ⊥ to grain		0.0016	640	
Liquids				
Water 25 deg. cent		0.0057	176	4
Paraffin oil		0.0014	710	8
Glycerin 25 deg. cent		0.0024	410	4
Petroleum 23 deg. cent		0.0016	630	8
Gases				
Air at 20 deg. cent		0.000249	4010	9
" " 100 deg. cent		0.000300	3330	9

REFERENCES:—1. C. P. Randolph, Research Lab., General Electric Co. (1912). 2. Jäger & Diesselhorst, Wiss. *Abl. d Phys.* Techn. Reichanstalt, 3, 269 (1900). 3. Lees, *Phil. Trans* (A) 183, 481 (1892). 4. Lees, *Phil.* Trans. A 191, 399 (1898). 5. Lees and Chorlton, *Phil. Mag.* (5), 41, 495 (1896). 6. Technical Report No. 10940. General Electric Company, by C. P. Steinmetz (1910). Experiments carried out by J. L. R. Hayden. 7. Paper on Heat Paths in Electrical Machinery read before the Institution of Electrical Engineers, Nov. 1911 by H. D. Symons and M. Walker. 8. R. Weber, *Ann. Phys.*, 11, 1047 (1903). 9. Langmuir, *Phys. Rev.* 34, 406 (1912). 10. A. Eucken, *Ann. Phys.* 34, 185 (1911). 11. Koenigsberger and Weiss, *Ann. Phys.* 35, 1 (1911).

In the above table it will be noted that all the metals and alloys have a very high thermal conductivity compared with that of non-metallic substances (with the exception of graphite). Practically all of the electrical insulators have a conductivity about one-thousandth of that of copper. The conductivities of various substances of any one type do not differ very greatly from one another; for example, the range of conductivities of organic materials used for electrical insulation is from about 0.0015 to 0.0040. The presence of air spaces in a body very much decreases the conductivity, as is seen for the extremely low conductivities of such materials as wool, cotton batting, etc. That this high thermal resistance is entirely due to the presence of gas, is evident

from the fact that these materials are relatively good conductors when placed in an atmosphere of hydrogen.

In the case of powdered or fibrous materials, the heat conductivity is practically independent of the true conductivity of the solid substance forming the grains or fibers. For example, finely divided metallic powders, such as zinc dust or tungsten reduced by hydrogen from finely divided oxide, are extremely good heat insulators, although the material itself is a good heat conductor.

The conductivity of liquids is quite low, and is in most cases very insignificant compared with the amount of heat carried through the liquid by convection currents. The figures given above for liquids can be used only for liquids through which heat is being transmitted downwards, or in the case where the liquid is held in the meshes of some fibrous material such as cloth. This is a common case, however, in electrical insulation.

The heat conductivity of gases is smaller than that of solids and liquids.

Temperature Coefficient of Heat Conductivity. Pure metals, although they have a large temperature coefficient of electrical conductivity, have a thermal conductivity which is practically the same at all temperatures. Alloys have a conductivity which usually increases somewhat with the temperature, the temperature coefficient being never greater than about 0.1 per cent per degree cent., and usually much less than this. In electrical machinery, therefore, with the relatively small temperature range involved, we may consider the thermal conductivity as independent of the temperature.

In the case of pure crystalline, non-metallic substances, Eucken (*Ann. d Physik*, Vol. 34, p. 185, 1911) has shown that the thermal conductivity varies approximately in inverse proportion to the absolute temperature. In other words, the temperature coefficient of such substances is usually about —0.33 per cent per deg. cent.

The same investigator has also shown that with amorphous, non-metallic substances, like glass, the conductivity increases slightly with increase of temperature, the temperature coefficient being about +0.15 per cent per deg. cent. Such substances as paraffin, ebonite, etc., are found to have practically no temperature coefficient.

Tests made by Mr. C. P. Randolph have shown that for powdered or fibrous materials the temperature coefficient of heat conductivity is very large. For example, measurements of the

heat conductivity of Poplox at various temperatures up to 500 deg. cent. gave the results:

Range of temperature	Heat Conductivity Watts per cm. per deg. cent.
20 – 100	0.00030
100 – 200	0.00039
200 – 300	0.00057
300 – 400	0.00076
400 – 500	0.00133

This material (popped water glass) had an apparent density of 0.026 and contained air cells of about 0.5 mm. average diameter. The large temperature coefficient is caused by radiation across the walls of the air cells which is relatively large at high temperatures but almost negligible at room temperature. Below 100 deg. cent. the temperature coefficient for powdered and fibrous materials may be taken as + 0.3 per cent for materials with a coarse structure and proportionately less for finer structure.

In the case of gases, the mobility and the coefficient of thermal expansion are so great that convection becomes very large. It was thought for a long time that gases had no true conductivity. Maxwell, however, calculated the conductivity from the kinetic theory, and predicted that it would be independent of the pressure. His results have since been thoroughly verified. To avoid convection currents, it is only necessary to reduce the pressure of the gas to a value of several centimeters of mercury. At lower pressures the heat conductivity is found to be entirely independent of the pressure, down to a pressure of one mm. When the pressure becomes much less than this, the free path of the molecules begins to become comparable with the length of the path along which the heat is conducted. At still lower pressures, the heat conductivity becomes proportional to the pressure. It is evident that the pressure at which the change from one of these laws to the other takes place is inversely proportional to the length of the path of heat flow. In the case, therefore, where we have the space subdivided by the presence of a fibrous material, we find that the heat conductivity does not remain constant down to such low pressures as one millimeter, but may even, with very finely divided materials, decrease with decreasing pressure, from atmospheric pressure down. This subject has been very fully treated by Smoluchowski [*Ans. Akad. Wiss. Krakau* (1910) A 129-153].

In the case of the heat conduction of gases, we find there is a

large temperature coefficient of heat conductivity. It has been thoroughly proven that Sutherland's formula

$$\mathbf{k} = \frac{K\,\mathbf{c}_v\sqrt{T}}{1 + \dfrac{C}{T}} \tag{2}$$

very accurately represents the change in conductivity with the temperature. Here K is a constant, $\mathbf{c}_v$ is the specific heat of the gas at constant volume and c is a constant equal to 124 for air. In general, when $\mathbf{k}$ is a function of the temperature, we cannot use equation (1) to calculate the heat conduction through a given body. It can be shown, however, [Langmuir, *Phys. Rev.* Vol. 34, p. 406 (1912)], that if we substitute for the factor $\mathbf{k}\,(T - T_0)$ the integral $\int_{T_0}^{T} \mathbf{k}\,d\,T$ we are then able to calculate the heat conduction, no matter how much the heat conductivity may vary with the temperature. For such cases as these, the results can be calculated most easily by calculating or plotting the values of the integral $\int_{T_0}^{T} \mathbf{k}\,d\,T$. If we represent by ϕ the value of this integral, which we may call specific conduction, then the formula for heat conductivity becomes

$$W = \frac{A}{l}\,(\phi - \phi_0) \tag{3}$$

Heat Conduction through Bodies of Various Shapes

Equations (1) or (3) can be used only for the heat conduction between parallel planes. In other cases, A and l are both variables, and the proper mean values must be determined, by special methods.

No matter what the shape of the body, the ratio $\dfrac{A}{l}$ has a definite value, if the surfaces of in-flow and out-flow of the heat are fixed. Let us call this quantity the "shape factor," and represent it by the letter s. Our equation for heat conduction thus becomes

$$W = s\,(\phi - \phi_0) \tag{4}$$

The value of the shape factor for bodies of various shapes may be of interest. In a paper to be published shortly (Langmuir, Adams, and Meikle, *Trans. Am. Electrochem. Soc.*, Vol. 24, 1913), methods for calculating the shape factor of bodies of many different shapes will be given. The following cases only are worthy of considering here:

Planes

$$s = \frac{A}{l}$$

Concentric Cylinders of Diameters a and b.

$$s = \frac{2\pi}{ln\frac{b}{a}} \tag{5}$$

Concentric Spheres of Diameters a and b.

$$s = \frac{2\pi}{\frac{1}{a} - \frac{1}{b}} \tag{6}$$

Concentric Rectangular Prisms or Parallelopipedons. For this case, the following formula applies with great accuracy to the flow of heat where the thickness of the heat-conducting material between the two surfaces is constant and where the thickness of the layer is not more than $2\frac{1}{2}$ times the smallest dimension of the prism, a condition nearly always fulfilled in practise. The formula is

$$s = \frac{A}{t} + \tfrac{1}{2}\Sigma l + 1.2\,t \tag{7}$$

Here t is the thickness of the layer of conducting material, Σl is the sum of the length of the 12 edges of the inner prism, and A is the total surface of the inner prism.

Radiation of Heat

Dulong and Petit (1817) gave an empirical formula for heat radiation which has been used very largely by engineers almost up to the present date.

The Stephan-Boltzman law that the radiation from a black body is proportional to the fourth power of the absolute temperature has been shown to be derivable from the second law of thermodynamics, and has withstood the tests of very careful experimental investigation. We may therefore look upon this law as being one of the exact laws of nature. It must be remembered, however, that it applies only to radiation from a so-called black body; that is, a body which absorbs all heat rays which fall on it. Such a body can only be approximately realized, and any actual body must radiate less heat than an ideal black body at the same temperature.

The Stephan-Boltzman law, as applied to the radiation from any given body, may be written

$$\mathbf{W} = 5.7\, e\left[\left(\frac{T}{1000}\right)^4 - \left(\frac{T_0}{1000}\right)^4\right] \tag{8}$$

Here, $\mathbf{W}$ is the energy in watts radiated per square centimeter of surface. T is the temperature of the hot body, and T_0 the temperature of the surrounding space, e we may call the relative emissivity of the body; it is always a number less than unity and is a characteristic property of the radiating body.

The radiation constant, 5.7, is subject to some uncertainty at present. For several years, the commonly accepted value was 5.32, which was the result obtained by Kurlbaum (*Wied. Am.* 65, 746, 1898). Recently, however (1909), Féry obtained a value 6.3. Since then many investigators have redetermined this constant. Paschen and Gerlach (*Ann. d Physik*, Vol. 38, p. 30, 1912) obtained the value 5.9. Shakespeare (*Proc. of the Roy. Soc.*, Vol. 86A, p. 180, 1911) obtained 5.67. Within the next year or so the correct value of this constant will undoubtedly be determined. For the present, it would seem almost certain that the value 5.32 is too low, and that the value 5.7 must be fairly close to the true value.

The radiation of heat differs from conduction and also convection in that it is a purely surface phenomenon. The amount of heat radiated is strictly proportional to the extent of the surface, and is independent of the presence of gas adjacent to the surface. From bodies that are not black, the heat radiated from cavities in the bodies has a greater intensity than that radiated from a flat surface, for the reason that from such a cavity there is not only the heat radiated from the bottom of the cavity, but also

that reflected by the bottom surface from the walls of the cavity. The above equation for radiation therefore applies only for heat that comes directly from a surface, and not for that which has been reflected from the surface. In general, however, this factor is not a difficult one to take into account in the consideration of heat radiation.

The most difficult question involved is the determination of the relative emissivity e. For clean polished surfaces of metals this quantity is small, ranging from 0.02 to 0.30. For non-metallic substances it is usually very much larger than this, ranging from about 0.3 up to about 0.9. The following table gives the values of e calculated by the writer from measurements made by C. P. Randolph. A detailed description of these measurements will be published in the *Transactions* of the Am. Electrochem. Soc., Vol. 23, 1913.

TABLE II

Copper, oxidized by heating to a red heat	0.74
Copper, calorized; that is, surface impregnated with Al	0.27
Silver, pure, polished	0.03
Cast iron, fresh machined surface	0.25
Cast iron, oxidized by heating to red heat	0.65
Aluminum paint on cast iron	0.47
Gold enamel on cast iron	0.39
Monel metal, polished	0.40
Monel metal, oxidized	0.45

The relative emissivities from highly polished metal surfaces can be calculated from the reflectivity of the surface for heat rays, the emissivity and reflectivity being complementary to each other. That is, the emissivity is equal to $1 - r$ where r is the reflectivity. There is a considerable amount of data in the literature on the reflectivities of metals for heat rays. However, it has been shown by Hagen and Rubens (*Ann. d Physik*, Vol. 8, p. 1, 1902) that the relative emissivity may be calculated by the formula

$$1 - r = e = 0.365 \sqrt{\frac{\theta}{\lambda}} \tag{9}$$

where θ is equal to the specific electrical resistivity in ohms-centimeter units at the temperature of the metal and λ is equal to the wave length of the radiant energy in centimeters.

Recent investigations have shown that this formula is very accurate for wave lengths exceeding 0.005 mm. in length. The average wave length of the light corresponding to any given

temperature is, according to Wien's radiation law, approximately $\frac{0.29}{T}$ cm. If we substitute this in the above equation, we obtain the value

$$e = 0.68 \sqrt{\theta T} \tag{10}$$

This equation enables us to calculate the relative emissivity for any highly polished metal up to about 500 or 600 deg. cent. However, because of surface oxidation, the emissivity will nearly always be much larger than this, except with such metals as silver, platinum, and gold.

Organic substances, such as oils, varnishes, resinous materials, have a very high emissivity; that is, between 0.8 and 1. Although in the visible spectrum these bodies are transparent, they are practically black bodies as regards the long heat rays that are involved in the radiation from bodies at ordinary temperature. The same is true of glass, this being practically a black body with respect to heat rays. Therefore, in calculating the amount of radiation from electrical insulating materials, we may very safely assume, whether these materials have a black color or a much lighter color, that they are nearly black bodies, as far as radiation is concerned.

The Temperature Coefficient of Radiation. For small differences of temperature, equation (8) may be written

$$W = 0.0228\, e \left(\frac{T_0}{1000}\right)^3 (T - T_0) \tag{11}$$

We thus see that the amount of radiation between two bodies having a given difference of temperature, increases in proportion to the third power of absolute temperature. This means that the temperature coefficient of radiation between two bodies differing only slightly in temperature, is + 1.0 per cent per deg. cent. This is at least three times greater than the temperature coefficient of heat conduction through solids or even gases.

Convection of Heat

The transmission of heat through liquids or gases takes place principally by means of currents set up in the fluid because of differences of density produced by the unequal heating. The amount of heat carried by convection depends on the velocity of the convection currents and also on the specific heat of the fluid. The currents are produced by the differences in density between

the fluid in contact with a hot body and in contact with the cold body. This difference will be proportional to the coefficient of thermal expansion and also proportional to the density of the fluid itself. The currents produced by these differences of density have to act against the force of viscosity, thus the more viscous the fluid, the lower will be the velocity of the currents. We may therefore say, in a general way, that the amount of heat carried by convection will be roughly proportional to the product of specific heat, density, and expansion coefficient, and will be aproximately inversely proportional to the viscosity of the fluid.

From the very nature of convection, we would hardly expect it to obey such simple laws as those of radiation. It will depend upon the shape of the hot body, the distance between the hot body and the cold body, and upon each of the factors mentioned in the paragraph above.

There have been a great many investigations made of the laws of convection of heat, especially in gases. Dulong and Petit, in 1817, derived several empirical laws which have been more or less verified over rather narrow ranges of temperature by Péclet, (1860). These laws are today used in many engineering handbooks as best representing the knowledge of convection of heat. Within the last thirty years, however, much more valuable work has been done, and we now know that the formulas of Dulong and Petit are only rough approximations.

Lorenz (*Ann. d Physik*, Vol. 13, p. 582, 1881) derived formulas for the convection of heat from vertical plane surfaces, making, however, certain rather arbitrary assumptions. He obtained the formula

$$\mathbf{W}_c = 0.548 \sqrt[4]{\frac{\mathbf{c}\, g\, \mathbf{k}^3}{\mathbf{h}\, H\, T}} \sqrt{\rho}\, (T_2 - T_1)^{5/4} \qquad (12)$$

where $\mathbf{W}_c$ = Heat convection per unit surface.
$\mathbf{c}$ = Specific heat of the gas at constant pressure.
$\mathbf{k}$ = Its thermal conductivity.
$\mathbf{h}$ = Its viscosity.
T = Its average temperature.
ρ = Its average density.
g = Gravitational constant.
T_2 = Temperature of plane surface.
T_1 = Temperature of the gas at a great distance from the plane.
H = Height of the plane.

Putting in the data for air, at room temperature, 27 deg. cent. and standard atmospheric pressure, this equation reduces to

$$W_c = 0.000399\, H^{-\frac{1}{4}} (T_2 - T_1)^{5/4} \qquad (13)$$

where W_c is expressed in watts per sq. cm., and H is in cm.

This equation agrees well (within five per cent) with the results calculated by the writer from the experimental results of C. P. Randolph on the convection of heat from disks of metal 7½ in. (19 cm.) in diameter. It is very probable, from the method of derivation of this equation, that the influence of the height of the plane on convection is not as great as indicated by the term $H^{-\frac{1}{4}}$ in the equation.

Boussinesq (*Comptes Rendus*, 132, 1382, 1901) has treated the mathematical theory of free convection and obtained formulas similar in form to those of Dulong and Petit. In a later paper (*Comptes Rendus*, 133, 257, 1901) he develops the theory of forced convection from plane surfaces as well as from cylinders, spheres and ellipsoids. In all such calculations the simplifying assumptions that need to be made render it necessary to subject the formulas to very careful experimental test before much reliance can be placed upon them.

Compan [*Ann. Chim. phys.* (7) 26, 488 (1902)] has made elaborate experiments on free convection from a copper sphere two cm. in diameter placed in hollow concentric spheres of various sizes. He worked at pressures ranging from a few thousandths of a mm. up to six atmospheres. He varied the temperature of the small sphere from 300 deg. down to 50 deg. He found that over this whole range of temperature and for pressures above 20 cm., the convection varied with the 1.233 power of the temperature difference and with the 0.45 power of the pressure.

Ayrton and Kilgour [*Phil. Trans.* 1892, abstract in *Proc.* Roy Soc. 50, 166 (1891)] have made elaborate investigations of the heat losses in air from very fine platinum wires [0.0012 to 0.014 inch (0.03 to 0.35 mm.) in diameter] at temperatures from room temperature up to 300 deg. cent. Their results were expressed in tables and empirical formulas only.

They found that the heat loss from the wires was nearly independent of the diameter of the wires.

Porter (*Phil. Mag.*, Vol. 39, p. 267, 1895) pointed out that this practical independence of the convection from the diameter of the wire may be accounted for by assuming that the heat is

carried from the wire principally by conduction. He derives some equations with three empirical constants, which agree excellently with Ayrton and Kilgour's results. However, he obtained values for the radiation from the wire and for the conductivity of the air which were totally different from those which we now know to be the true values. His formulas must be looked upon, there fore, practically as empirical formulas.

A. Russell [*Phil. Mag.* 20, 591, (1910)] recalculated the results of Boussinesq (*loc. cit.*) and put them in a practical form. These are purely theoretical equations which give the heat lost by convection from cylinders and planes in currents of gases or liquids.

The writer (*Phys. Rev.*, Vol. 34, p. 401, 1912) showed that the free convection of heat from small wires consisted essentially of conduction through a film of gas of definite thickness. It was shown experimentally that the thickness of the film is independent of the temperature from 100 deg. cent. up to the melting-point of platinum. The thickness of this film depends on the diameter of the wire, but in such a way that it may be calculated with no other data than the diameter of the wire and the diameter which the gas film would have in the case of convection from a plane surface. To calculate the heat lost by convection from any wire, all that is required is to know the coefficient of heat conductivity of the gas and the thickness of this gas film for a plane surface, this latter being a constant quantity characteristic for a gas at any given temperature and pressure.

It was shown [Langmuir, TRANSACTIONS, A. I. E. E., p. 1229 (1912)] that the formulas derived from this film theory agreed excellently with the experimental data of Kennelly (TRANSACTIONS A. I. E. E., Vol. 28, p. 363, 1909) on the convection of heat from small copper wires in air at various pressures and in air moving at different velocities.

In the following pages the writer has attempted to give the principal laws for the convection of heat under the different conditions which influence it.

Free Convection. The film theory of convection makes it possible to calculate the convection from plane surfaces, from cylinders or wires of any diameter, and from spheres.

In the case of plane surfaces, the heat lost by convection is calculated simply by considering that there is a layer of air 4.3 mm. thick, adhering to the surface, and through which the heat has to be carried by conduction. It must, of course, be remembered that in addition to this heat loss by convection, there is the heat lost by radiation.

This film theory fully explains the fact that for wires of very small diameter the heat lost by convection is nearly independent of the diameter. This follows from the shape factor (see equation **5**) for concentric cylinders, since the logarithm of a number varies only slowly as the number increases.

The amount of convection from the surface differs only slightly, whether the surface is placed vertically or horizontally. With a surface placed in the latter position, so that it is exposed to the air above it, the heat lost by convection is about 10 per cent greater than when the surface is placed vertically. With the surface horizontal, but inverted so that it must lose its heat downward through the air, the heat lost by convection is naturally considerably less. For a 7½-in. (19-cm.) disk, placed in this position, the heat loss was actually found to be only 50 per cent of the heat lost when the surface is placed vertically.

The amount of convection from a surface probably does not depend, to any great extent, on the nature of the surface. At least, so far as the writer knows, there is no trustworthy experimental evidence that the surface has any influence.

It is a surprising fact that between the temperatures 100 and 500 deg. cent. the convection calculated from the film theory as above outlined, gives nearly identical results with those calculated by Lorenz's formula (see equation **12**). At temperatures above 500 deg. cent., both for convection from plane surfaces and from wires, the convection calculated from the film theory agrees better with the experimental facts than that calculated from Lorenz's formula. At temperatures much below 50 deg. the two formulas begin to diverge quite widely. The film theory would indicate that the convection would fall off practically linearly as the temperature difference decreases; whereas, according to Lorenz's equation, the temperature would be proportional to the 5/4th power of the temperature difference. This would mean that for very slight differences of temperatures—for example, 5 or 10 deg.—that Lorenz's equation would give very much lower results than would be obtained from the calculation from the film theory.

To decide which of these two theories would give the correct result for very small temperature differences, will require careful experimental investigation. Probably the bulk of the evidence at present is in favor of Lorenz's equation.

It should be pointed out that there is no theoretical reason known why the thickness of the film should remain constant, as the temperature of the wire or plane varies. This is simply an

experimentally determined fact at temperatures above 100 deg. cent. It is quite possible that for very small temperature differences, the film thickness might become greater. In any case, however, the variation in the film thickness down to temperature differences as low as 30 deg., would not be important in most calculations of heat convection.

Effect of Pressure on Free Convection. The heat conductivity of gases is independent of the pressure. According to the film theory, therefore, the effect of pressure on the amount of heat convection would depend simply upon the effect of pressure on the film thickness, which we will call B. Theoretically, it would be very difficult to determine exactly what this effect would be. But it is certain that as the density of the gas decreases by the reduction of pressure, the thickness of the film B would increase; not necessarily in inverse proportion to the pressure, however.

From Kennelly's data the writer found that B varied in inverse proportion to the 0.75 power of the pressure. From some recent experiments with small wires in air, over a wide range of pressure, the writer finds that B varies more nearly in inverse proportion to the first power of the pressure. From small wires, however, the amount of heat convection depends only slightly upon the diameter of the film. In these experiments, therefore, it is very difficult to find accurately the law according to which the film thickness varies with the pressure. As the size of the wire decreases, the convection becomes less and less sensitive to pressure changes.

For the effect of pressure on the convection from plane surfaces, there is only very meagre experimental data. Compan, in studying the convection from spheres 2 cm. in diameter, concludes that the convection varies with the 0.45 power of the pressure. According to Lorenz's equation, the amount of convection from plane surfaces would be proportional to the 0.5 power of the pressure. This would be equivalent to saying that B varies in inverse proportion to the 0.5 power of the pressure.

To decide exactly how convection varies with pressure, we require further experimental work on plane surfaces in air at various pressures. Provisionally, it is probably safe to say that for the convection from plane surfaces or wires, the value of B is inversely proportional to the 0.5 power of the pressure.

Effect of Temperature on Free Convection. From experiments by the author on convection from platinum wires in air at various temperatures from − 180 up to 700 deg. cent., it would appear that the film thickness for a plane surface is approximately proportional to the absolute temperature.

The temperature coefficient of heat convection for small wires will simply depend on the temperature coefficient of the heat conductivity of the air, since in this case the amount of heat convection depends so slightly on the film thickness. From Sutherland's equation (**2**) it may be shown that in the neighborhood of room temperature, the heat conductivity of air increases approximately in proportion to the 0.76 power of the absolute temperature. This would mean that the temperature coefficient of heat conductivity at room temperature is + 0.25 per cent per degree, and this would be the temperature coefficient of heat convection from the wire.

In other words, more energy would be required to maintain a wire at a given temperature elevation above its surroundings, the greater the temperature of the surroundings.

It is quite different with the convection of heat from plane surfaces. Here, the convection depends not only on the heat conductivity of the air, but also on the thickness of the film. Since the latter varies proportionally to the temperature, the amount of convection from plane surfaces will be proportional to

$$\frac{T^{0.76}}{T} = T^{-0.24}$$

In other words, the temperature coefficient of the heat convection will be − 0.08 per cent per deg. cent. From plane surfaces the convection with a given temperature difference decreases slightly with increasing air temperature.

Lorenz's equation would lead to the temperature coefficient of − 0.37 per cent per degree, for convection from plane surfaces.

Forced Convection. The effect of air currents on convection is very great, as is well known. However, the air currents that occur in an ordinary room, at some distance from the windows, have only very slight effect on the convection from wires and plane surfaces heated to several hundred degrees. By placing a few large screens around the body, very consistent results are obtained. With higher wind velocities, such as those obtained by placing an electric fan close to the body, the amount of convection, both from plane surfaces and from wires, increases about four-fold. Measurements with an anemometer showed the wind velocity in this case to be about 400 cm. per second.

Kennelly has investigated the effect of wind velocity on convection from small wires, and has found that the amount of convection varies approximately in proportion to the square root

of the velocity. For velocities from 300 to 1800 cm. per second, he finds that the convection is proportional to the quantity

$$\sqrt{\frac{v + 25}{25}}$$

That is, the convection of any given wind velocity can be calculated from the velocity in quiet air by multiplying by the above factor. From some very rough experiments by the writer, on convection from plane surfaces and also from some calculations from published data (see article in *Trans.* Am. Electrochem. Soc., Vol. 23, 1913,) the amount of convection is again found to vary with the square root of the velocity, and the above factor is found to be

$$\sqrt{\frac{v + 33}{33}}$$

Compan, in his experiments on spheres, finds that the convection varies with the square root of the velocity. Boussinesq has also arrived at the same conclusion from theoretical calculations.

From Kennelly's results, the writer drew the conclusion that the film thickness varied inversely as the 0.75 power of the velocity. This gave results agreeing well with Kennelly's data, but it has been found that the film thickness, in the case of forced convection from plane surfaces, is very different from that found for small wires in wind of the same velocity. This fact renders the film theory almost useless in cases of forced convection.

The best single equation for the calculation of convection of wires is probably an equation calculated by Russell (*loc. cit.*) by the method first given by Boussinesq. This equation is

$$\mathbf{W} = 8 \sqrt{\frac{\mathbf{c}\,\rho\,\mathbf{k}\,v\,a}{2\,\pi}}\,(T_2 - T_1) \qquad (14)$$

where $\mathbf{W}$ = Convection loss per unit of length from the cylinder.
$\mathbf{c}$ = Specific heat of the gas or liquid at constant pressure.
ρ = Density of the fluid.
$\mathbf{k}$ = Heat conductivity.
v = Velocity.
a = Diameter of the cylinder.
$T_2 - T_1$ = Difference of temperature between the cylinder and the fluid.

If, in this equation, instead of the coefficient 8 in front of the radical sign, we place 5 or 6, we find that the results agree well with Kennelly's experimental data. On the other hand, for large cylinders from 2 to 10 cm. in diameter, the formula gives good results with the coefficient between 7 and 8.

In the case of forced convection in air at room temperature, equation (**14**) reduces to

$$\mathbf{W} = 0.000180\, C \sqrt{V a}\, (T_2 - T_1) \text{ watts per cm.} \qquad (\mathbf{15})$$

where c is the number that varies from 5 to 8, according to the size of the wire, as described above.

From equation (**14**) we can calculate that with a given difference of temperature and given wind velocity, the amount of convection would vary with

$$\sqrt{T^{-1+0.76}}$$

This would mean that forced convection under these conditions would have a temperature coefficient of -0.04 per cent per degree; that is, with a given difference of temperature, the amount of convection would decrease slightly as the temperature of the air increases.

If the velocity of the air is produced by centrifugal force, as it often is in electric machinery, the velocity of the air currents will probably decrease as the air temperature increases, since the density decreases and the viscosity increases. The effect of this would be to make the temperature coefficient numerically still greater.

If the convection currents are caused by flue action (for example, because of heat given to the air in long passages), this effect will be still more marked, so that the temperature coefficient will be strongly negative.

In problems on convection of heat, the flue action is often very important. For example, in studying the convection from a horizontal, plane disk, 7½ in. (19 cm.) in diameter, we find that if we place a cylinder of asbestos paper about 10 in. (25 cm.) in diameter and 6 in. (15 cm.) high, around the disk, the convection is nearly doubled when the disk is at about 150 deg. At higher temperatures the effect of the cylinder becomes relatively much less. By observing the motion of smoke in the air above the heated disk, it is seen that the air descends along one side of the cylinder, moves across the disk, and rapidly rises

along the other side of the cylinder. In general, with vertical surfaces of considerable height, any means of preventing horizontal air currents from flowing in towards the middle portion of the surface will tend to increase the convection, since it causes the air to be drawn over the lower portion of the surface with very much increased velocity. However, if such flues as are made in this way are too long, the convection again tends to decrease, since the air that comes in contact with the upper part of the surface is already heated by flowing along the lower part of the surface, and is therefore capable of taking up very little additional heat.

The whole subject of flue action in convection is as yet very little understood, and should be the subject of further careful experimental investigation.

Convection in Liquids. The convection in liquids, in principle, at least, does not differ radically from that in gases. However, the velocity of the currents set up is very much less than in the case of gases, but because of the very great heat capacity of liquids per unit volume, as compared with gases, the amount of heat carried by convection is usually much greater than with gases. The effect of the viscosity is usually of much more importance than in the convection of gases.

The viscosity of liquids, as a rule, decreases very rapidly with increase in temperature, so that the temperature coefficient of free convection in oil is always positive and has a very large value, but differs greatly for different oils.

In oil-cooled transformers, the importance of this effect was clearly pointed by S. E. Johannesen (The Effect of Different Air Temperatures on Temperature Rise of Electrical Apparatus, *The Rose Technic*, Rose Polytechnic Insitute, Terre Haute, Ind., Nov., 1904). To quote from this article:

> It is well known that a transformer immersed in thin oil will run cooler than one immersed in thick oil, all other conditions being the same, and further, a transformer immersed in paraffin (poured while hot and allowed to solidify) would burn out if operated at a room temperature of 0 deg. cent., and there would even be danger if it were operated in a room having a normal temperature; but when immersed in a light oil and run in a room having a normal temperature of even say 35 deg. cent., it would operate within safe heat limits. This experiment has been tried.
>
> Specific heat of liquids differs very little at different temperatures, their power to absorb heat being approximately the same at any temperature within the working range of electrical apparatus. Therefore, the efficiency of a liquid acting as a cooling medium (when confined) depends upon its ability to flow, assuming that the points of absorption and dissipation are equally efficient.

The table below is given as an illustration to show approximately the heat which would be dissipated at various room temperatures, and fairly represents results of a heat run of a 100-kw., 60-cycle, 2000-volt, oil-insulated, self-cooling transformer.

Room temperature	Actual temperature rise	Loss at max. temp. rise, watts
5 deg. cent.	60 deg. cent.	1154
25 "	50 "	1191
35 "	45 "	1210

He points out for the class of oil-cooling apparatus that the Institute rule does not apply, as it gives a correction which is in the wrong direction.

Combined Effects of Radiation, Convection and Conduction

The heat lost by surfaces is equal to the sum of the heat radiated and the heat carried by convection. It may be of interest to calculate the relative magnitude of these two effects under various conditions. For a surface only slightly above room temperature in air at 20 deg. cent., we may calculate the heat lost by convection by determining the amount of heat that would be conducted through a layer of air 4.3 mm. in thickness. For one degree temperature difference the heat carried through such a film would be equal to the heat conductivity of the air, *i. e.*, 0.00025, divided by the thickness of the film in centimeters. This gives 0.00059 watt per sq. cm. per deg. cent. as the convection from a body in the neighborhood of room temperature.

For a body at 100 deg. cent., taking a mean conductivity over this range as 0.000275, we find in a similar way the convection to be 0.00064 watt per sq. cm. per deg. cent.

From equation (**11**) the radiation from a black body only slightly above room temperature (20 deg. cent.) is 0.00057 watt per sq. cm. per deg. cent. From equation (**8**), considering the radiation from a black body at 100 deg. cent. in surroundings of 20 deg. cent., we find the radiation to be 0.00086 watt per sq. cm. per deg. cent.

The total loss of heat from a surface will be simply equal to the sum of the convection and radiation. For most purposes, it is more convenient to deal with surface resistivities, rather than with surface conductivities. The resistivities are obtained by taking the reciprocal of the sum of the radiation and convection. In the following table are given the surface resistivities

of plane surfaces, in three different positions, vertical, horizontal with exposed surface above, and horizontal with exposed surface below. In each case the resistivity at 20 deg. and at 100 deg. is given. Also, the resistivity for the case of a body which does not radiate any heat, and the resistivity for a body radiating as much as a black body. Any actual body will, of course, have a resistivity which lies between these two extremes.

There are some cases where the radiation of heat does not play any part in the heat loss from surfaces. For example, in the interior of machines the circulation of air may carry away heat, yet no heat will be lost by radiation. In this case, the surface resistance will be independent of the nature of the surface and will be that given in the table for a case of no radiation.

The effect of air circulation will always be to cut down the surface resistance, but even with relatively high wind velocities,

TABLE III

SURFACE RESISTIVITIES OF PLANE SURFACES

Position	20 deg. cent.	100 deg. cent
Vertical		
No radiation	1700	1560
Full radiation	860	670
Horizontal, exposed above		
No radiation	1540	1430
Full radiation	820	640
Horizontal, exposed below		
No radiation	3400	3100
Full radiation	1150	850

this effect will never cut it down to less than about one-fifth of its value with no wind.

Another important case, where the effects of radiation and convection need to be separated, is in determining surface losses from a piece of apparatus in a room in which the walls are at a different temperature from the air. It is readily seen that if the average temperature of the walls of a room is 10 deg. above the temperature of the air surrounding the piece of apparatus in the room, the apparatus will receive heat by radiation which it must give up by convection. Since at room temperature radiation and convection are about equally effective in removing the heat from a body which is a good radiator, it is evident that the machine will reach a temperature which is about half way between that of the air and that of the walls; that is, the temperature of the surface of the machine will be about five deg. above that of the

air surrounding it. Similarly, if the walls are colder than the air, the machine will have a temperature lower than the air. It will be readily appreciated that this effect is by no means negligible, since the walls of a room are often 10 deg. warmer or colder than the air. For example, the roof may be heated by the sun's rays and the air in the whole upper part of the room may be very warm, whereas the air in the lower part of the room may be very much colder. Placing paper or cheese-cloth screens around the machine will almost completely prevent this difference of temperature of the air and machine.

As we have seen, small bodies, such as wires, take up the temperature of the air very much more readily than large bodies, and therefore this effect of radiation from the walls will be negligible in the case of wires.

We have seen that the combined effect of radiation and convection is equivalent to that of a surface resistance which may vary from about 600 to 1700. This resistance is equivalent to that of a layer of from 23 to 65 meters of copper or to a layer of from 1 to 3 cm. of rubber.

In calculations of the flow of heat through apparatus it is usually most convenient to determine the thermal resistance of the solid parts and simply add the surface resistance. If we then multiply the result by the number of watts of heat flow we obtain the total drop in temperature from the outside of the machine to the air surrounding it. Of course in actual machines it will usually be very difficult to calculate the thermal resistance of the solid parts. In any case, however, a knowledge of the relative importance of the various factors will be a long step towards the solution ot the problem.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

CURRENT RATING OF ELECTRIC CABLES

BY RALPH W. ATKINSON AND H. W. FISHER

At the request of the Standards Committee this paper has been prepared, the object being to present data relative to the carrying capacity of cables, which will be of value to engineers and users of cables. Especial attention is called to Table I (to be explained later) which gives data relative to the overload capacity of cables which have been working at different percentages of the normal carrying capacity. This question comes up frequently, engineers asking what per cent of overload can be applied to different cables. The per cent of such overload must of course depend upon the per cent of normal load at which the cable has been operating for several hours previous to the application of the overload. It is hoped that the formulas presented will be of value to engineers who have to deal with the subject under consideration.

The current rating of an electric cable depends entirely upon allowable heating, and is often more dependent upon or limited by external conditions than upon conditions intrinsic in the cable itself. On account of the extreme variability of these external conditions, the current rating of any given cable may be reduced to a half or a third, or even a small fraction of its normal rating. The time during which a cable may carry any given per cent overload is shorter than the time during which most other electrical apparatus can carry the same per cent overload. The allowable overload for any given duration of time depends simply upon the rate at which the cable will be heated to its limiting temperature. This is much more dependent upon the properties of the cable itself, than is the ultimate carrying capacity.

Very many formulas have been given as representing the carrying capacity of cables, beginning with the old rules which allow a certain number of circular mils per ampere. There is only one simple formula connecting the carrying capacity of conductors of different cross-sectional area which we have found useful and accurate. For nearly all conditions, it may be stated that the carrying capacity varies as the 1.3 power of the diameter of the equivalent solid conductor.

We will first discuss the limiting temperature. When insulating material is maintained at an excessive temperature, the first noticeable permanent change is in brittleness. It is sometimes important that this is true and that the first change is not in dielectric strength or, in fact, in tensile strength. A cable will sometimes work satisfactorily long after the insulation is badly injured by overheating, but only as long as it is undisturbed. The insulation of most non-rubber-insulated cables will stand a temperature of 150 deg. cent. for a very brief time without apparent permanent injury. If this temperature is maintained for more than a very short time, a matter of minutes, permanent injury results.

The limiting temperature is very much lower than this when it is maintained for a long period. To insure that progressive deterioration does not take place, the maximum temperature has been set by some as 65 deg. cent. and by others at 75 deg. For rubber, the temperature limit is lower and has been set at 50 deg. cent. For high-voltage cables, 6000 volts working pressure and above, another factor must be considered. The dielectric loss increases rapidly at the higher working temperatures, thus causing material additional heating. By some it has been said that the dielectric strength is much less at high temperatures, but we believe that this opinion was conceived because of the greater dielectric loss at high temperatures. A temperature limit of 50 deg. cent. has been named as the limit for high-voltage fibrous insulated cables. We believe that a temperature of 65 deg. cent. will not injure paper-insulated cables, but the increasing dielectric loss with increasing temperature must be considered and no exact rule can be given, as some insulating materials have a very considerably lower dielectric loss at high temperatures than others. We most earnestly hope to hear a thorough discussion of this question.

The temperature rise of a cable may be considered to be made up of:

1. The rise of copper above lead.
2. The rise of lead above immediate surroundings.
3. The rise of temperature of the surroundings due to the presence of the cables in the neighborhood.

It is only by an analysis of these elements that a general knowledge of temperature rise under all conditions can be obtained without experiment under any specific conditions for which information is desired. We intend to devote our attention to the first two elements of temperature rise in the present paper, these being the ones which are most nearly independent of variable external conditions. (For data concerning the other conditions we would refer to a paper read before the British Institution by Melsom and Booth in 1911. This paper also contained reference to a number of others. We would refer also to pages 213, 214 and 215 of Foster's "Electrical Engineer's Handbook," these data being based upon former experiments by one of the authors). We will take up individually the two elements to be considered.

The rise of copper above lead is equal to

$$t_1 = n\, b \log D/d \; \frac{I^2 \times 1000}{C.\,M.} \text{ deg. cent.}$$

where D/d is the ratio of the inside diameter of the lead sleeve to the outside diameter of the copper conductor.

I is the current flowing in the conductor.

$C.\,M.$ is the cross-sectional area of the cable in circular mils.

b is an empirical "constant" which depends upon the kind of insulation and somewhat upon the temperature. For practical purposes, it may be taken, for either paper-insulated or varnished-cloth-insulated cables, as 0.15. (See below for value for triplex cable.)

n is the number of conductors.

This formula may be applied directly to the case of concentric cables simply by adding the temperature rise from copper to copper and from copper to lead, remembering that the heat from two or from three conductors must pass through the outer layer of insulation.

For flat duplex cables, the temperature rise may be taken as about 15 per cent greater than that of a single-conductor cable with the same thickness of insulation. For triplex or round duplex cables we can use this formula if we use, for d, the diameter of the circle circumscribing the three conductors. We must also

use a different value of "constant." By experiment, this has been found to be from 0.16 to 0.185, the latter value being for cables where the insulation is very thin, relative to the size of the conductor.

The rise of lead above air or surrounding objects is

$$t_2 = n\,a\,\frac{I^2 \times 1000}{d_1\,C.\,M.}\ \text{deg. cent.}$$

Where d_1 is the outside diameter of the lead sheath in inches a may be taken as 0.06. This value applies where a clean bright lead sheath is suspended in free air. The value of a changes considerably with the size of the sheath, being less when the diameter is small. Preventing the natural circulation of air, increases a, while even a slight forced circulation decreases it materially. A rough, black coating on the lead will also reduce the value of a. For a flat duplex cable, use the formula as for a single conductor and increase the temperature rise of cable about 20 per cent.

It is very interesting that the temperature rise of a cable is very nearly the same, regardless of the thickness of insulation. This is because the change of the rise of lead above air counterbalances the change in the rise of copper above lead when the thickness of insulation is changed. Moreover, the experiments upon the rise in temperature of cables in air, of which these formulas are an expression, show practically the same temperature rise for a cable suspended freely in air as previous experiments show for a cable of the same kind laid in a duct system, no other cables being present. The table on page 215 in the previously mentioned section of Foster's Handbook may be used directly to give the carrying capacity of a three-conductor cable in free air when the permissible temperature rise is 45 deg. cent. The values should be increased one-third for single-conductor cables. Thus we see that not always do wide variations materially affect the carrying capacity of cables.

The temperature rise of a bare conductor in free air follows a very simple and easily derived law very closely. We may neglect the variation of a number of factors, the variation in the specific heat and in the proportionality between heat radiated and temperature difference, and may even neglect, for most practical purposes, the variation in the resistance of the copper. The effect of the last-named variation is in the opposite direction from that of

each of the others and accordingly is very nearly counterbalanced by them. Tests show that the following law is quite closely obeyed:

$$x = T - \frac{T}{e^{ta}} \quad \text{or} \quad e^{ta} = (10)^{ta/2.3} = \frac{T}{T - x}$$

x is the rise in temperature after t minutes.

T is the temperature which would be attained by the cable after an infinite time, supposing in the calculation of this temperature that the same factors mentioned above are constant until the temperature is reached.

$$a = \frac{\text{temperature rise per minute at the beginning}}{\text{ultimate temperature rise}}$$

$$= \frac{\left(\frac{I \times 1000}{C.\ M.}\right)^2 \times 2.06}{T},$$

and is constant for a given conductor.

e is the base of the Napierian system of logarithms.

This same type formula can be applied to insulated cables if we introduce an empirically determined constant, one which can be partly verified by theory.

The formulas then become

$$e^{ta/r} = (10)^{ta/2.3r} = \frac{T}{T - x}$$

The constant r represents the ratio between the heat which is stored in the entire cable and the heat which is stored in the copper.

The constant r varies with different styles of insulation and with their thickness relative to size of conductor. It also varies in the same cable, according to the time which is given for heat to penetrate into the insulation.

The constant r varies from practically one, with a very thin insulation, to three or more in a cable having a very small conductor with thick insulation. Based upon this formula and empirically determined values for r, we have calculated Table I given herewith.

To determine the time during which a three-conductor cable may carry a given per cent overload, use the table as for a single-

conductor cable having twice the cross-section area. For a two-conductor cable use the table as though for single-conductor cable of 50 per cent greater cross-section.

This table applies equally as well when the rating of a cable is changed by a change of temperature limit or by a change of initial temperature. The change in time for which an overload may be carried, caused by different thickness of insulation, will seldom be important. We have assumed in making the tables that

TABLE I

OVERLOAD CARRYING CAPACITIES OF CABLES

A Per cent	No. 6 B. & S. gage			No. 4 B. & S. gage			No. 2 B. & S. gage			No. 0 B. & S. gage		
	80%	50%	0%	80%	50%	0%	80%	50%	0%	80%	50%	0%
	Time in minutes			Time in minutes			Time in minutes			Time in minutes		
200	0.6	1.3	1.8	0.8	1.6	2	1	2.2	2.9	1.5	3.1	4.5
175	0.9	2	2.7	1.2	2.5	3	1.5	3.2	4.5	2.3	5	6.5
150	1.6	3.2	4.5	2	4	5.5	2.7	5.5	7	4	8.5	10
125	3.5	7	8.5	4.5	9	11	6	12	15	9	16	20
Per cent	No. 000 B.&.S. gage			300,000 cir. mil.			500,000 cir. mil.			700,000 cir. mil.		
	80%	50%	0%	80%	50%	0%	80%	50%	0%	80%	50%	0%
	Time in minutes			Time in minutes			Time in minutes			Time in minutes		
200	2.1	4.5	6	3.2	7.5	9.5	5	10	13	6	12	15
175	3.2	6.5	9	5	11	13	7	14	17	8.5	16	22
150	5.5	12	15	9	16	20	12	21	26	14	26	33
125	13	23	28	18	31	39	23	40	45	28	50	60
Per cent	1,000,000 cir. mil.			1,200,000 cir. mil.			1,500,000 cir. mil.			2,000,000 cir. mil.		
	80%	50%	0%	80%	50%	0%	80%	50%	0%	80%	50%	0%
	Time in minutes			Time in minutes			Time in minutes			Time in minutes		
200	7.5	15	19	8.5	17	22	11	21	26	12	24	30
175	11	22	27	13	25	31	16	30	36	18	34	40
150	18	33	41	20	37	45	25	46	55	28	50	65
125	35	60	73	40	70	85	50	80	95	55	95	110

5/32-in. (3.97-mm.) insulation is used. The table applies approximately for any of the styles of insulation with which lead cables are now insulated.

The data given are the lengths of time during which the loads given in the left-hand column can be carried, when the loads given in the first horizontal line of each table have been continuously applied previously to the application of the overload. Load is expressed in per cent of continuous carrying capacity, that is, normal load.

It must be noted that a considerable variation in the time frequently makes only a few degrees difference in the temperature This is most particularly true where the tables are hardest to interpolate closely.

Table II gives the time required to attain about 90 per cent of final temperature.

TABLE II

Size	Hours
No. 6	¾
1	1
No. 000	1¼
cir. mils	
300,000	1½
500,000	2
700,000	2¼
1,000,000	3
1,500,000	3¾
2,000,000	4½

It will require 50 per cent longer time to attain 97 per cent of final temperature and will require 50 per cent less time to reach about 68 per cent of final temperature.

The time given in this table may also be taken as the time interval which must elapse between overloads. If repeated oftener, the allowable duration of overload is decreased. If repeated at intervals of one-half this time, the allowable duration of overload is decreased 35 per cent.

We give an example of the use of these tables. It is required to determine the time an 800,000-cir. mil cable can carry 1200 amperes, when it carries continuously 400 amperes, its continuous capacity being given as 650 amperes. Express the loads as 185 per cent and 62 per cent of normal rating. We find from the tables that this load may be carried for about 11 minutes at intervals of 2½ hours.

For excessive overloads, we suggest that the temperature rise be calculated by the formula

$$\text{temp. rise} = \left(\frac{I \times 1000}{C.\,M}\right)^2 \times 1.15 \text{ deg. cent. per minute.}$$

The time required to reach the limiting temperature is then found directly.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 26, 1913.

Copyright, 1913. By A. I. E. E.

THE HEATING OF CABLES CARRYING CURRENT

BY SAUL DUSHMAN

The problem of determining the current-carrying capacity of a cable or wire for a given rise of temperature has been the subject of a number of investigations since the appearance of the classical paper by Professor Forbes in 1884. That, however, the last word has not been said on this subject is evidenced by the fact that during 1910 and 1911 an elaborate investigation was carried out at the National Physical Laboratory, England, at the request of the Wiring Rules Committee of the Institution of Electrical Engineers.[1]

While the present investigation was undertaken mainly with the object of obtaining data for calculating the carrying capacity of a special type of cable, it has been thought that a description of the methods used as well as the publication of some of the results obtained might be of interest in connection with the general subject of heat losses.

I. Description of Method

The carrying capacities of insulated cables may be determined either directly or indirectly. In the former case the actual rise in temperature is determined for a given current either by noting the increase in resistance of the conductor (*e.g.*, Melsom and Booth,) or by means of thermocouples placed in thermal contact with the conductor itself. By carrying out tests with a number of different sizes under varying conditions of temperature rise,

1. S. W. Melsom and H. C. Booth, The Heating of Cables with Current. *Journal* Inst. Electrical Engineers (Eng.) 47, 711-751 (1911). A fairly complete list of references to previous investigations will be found at the end of their paper.

an empirical relation is obtained, from which the carrying capacity may be calculated for any given rise in temperature.

In the indirect method the carrying capacity is calculated from the thermal resistivity of the insulation and the emissivity of the surface. The method has the obvious advantages of requiring a far smaller number of experimental data and of being much more generally applicable, especially in those cases where the design of fresh cable insulations is involved.

TABLE I

NOMENCLATURE

d = Diameter in inches of conductor.

D_1 = Diameter over first layer of insulation.

D_n = " " nth " " "

S = Cross-section of conductor, in square inches.

$= \nu \times \delta^2 \times \pi/4$ for stranded conductors.

ν = Number of wires in stranding.

δ = Diameter of individual wire in inches.

π = 3.1416

T = Maximum rise in temperature in deg. cent.

Θ = Temperature rise (variable).

x = Distance from heated end, in inches.

R = Electrical resistance per 1 inch of conductor, at 25 deg. cent.

$$= \frac{0.691 \times 10^{-6} \times 1.02}{S} \text{ for stranded conductors.}$$

$$= \frac{0.691 \times 10^{-6}}{S} \text{ for solid conductors.}$$

R_T = Electrical resistance per 1 inch at $T + 20$.

$$= \left(\frac{258 + T}{263}\right) R$$

K_1 = Thermal resistivity (*in deg. cent. per watt per inch*) of material of first layer.

H = Surface resistivity (in deg. cent. per watt per square inch).

K_n = Thermal restivity of material of nth layer.

r_n = Thermal resistance of nth layer of insulation per 1 inch length of cable.

$$= 0.365\, K_n \log \frac{D_n}{D_{n-1}}$$

Σr = Total internal thermal resistance of insulation per 1 inch length.

r_e = external resistance per 1 inch length.

$$= \frac{H}{\pi D_n}$$

W = Permissible watts per one inch length for rise of 1 deg. cent.

$$= \frac{1}{\Sigma r + r_e}$$

i = Current in amperes.

C = Heat capacity of cable per 1 inch length, in *watts*.

b = "Constant" in equation for rate of heating.

$$= \frac{60\,W}{C}$$

It is evident that after current has been passing through the conductor for a certain interval of time, a stationary state is attained at which the heat generated per unit length of cable is completely conducted through the insulation and dissipated at the surface. Under these conditions,

$$i^2 R_T = \frac{T}{\frac{2.3}{2\pi}\left[K_1 \log \frac{D_1}{d} + K_2 \log \frac{D_2}{D_1} + \ldots\right] + \frac{H}{\pi D_n}} \tag{1}$$

The nomenclature used in this and the following equations is that given in Table I.

Equation (1) may be written in the more convenient form:

$$i^2 R_T = \frac{T}{\Sigma r + r_e} \tag{2}$$

Data on the heat resistivity of electrical insulations have been published by H. D. Symons,[2] Professor Porter[3], C. P. Randolph[4] and A. Winkelmann[5].

Regarding H, it is known that for a "perfect" radiator the

2. *Journ.* Inst. Electrical Engineers (Eng.) read Nov. 29, 1911.
3. *Phil. Mag.* 20, 511 (1910).
4. *Trans.* Am. Electrochem. Soc. 21, 545 (1912).
5. Handbuch der Physik, III. 504, (1906).

value may be as low as 100 (expressed in degrees centigrade per watt per square inch), while for imperfect radiators it becomes as high as 200.

The great difficulty in applying equation (1) consists in determining what value of H should be used, since it varies so greatly with the nature of the surface. Furthermore, the data obtained for K on the insulation itself by the usual methods for determining heat conductivity may be altogether different from the value for the insulation on the cable, owing to conditions of manufacture.

In view of these considerations a method was adopted for determining the terms Σr and r_e [equation (2)] separately on the cable itself. Knowing the values of d and D for the cable it is then possible to calculate Σr and r_e for all other sizes.

This method, originally used by Despretz, is described in standard works on heat[6]. If we heat one end of a piece of cable which is so long that the other end always remains at room temperature, the relation existing at the stationary state between the rise in temperature, θ, and the distance, x, from the heated end, will be given by the differential equation

$$\frac{d^2\theta}{dx^2} = \mu^2 \theta^p \tag{3}$$

where

$$\mu^2 = \frac{K'}{S(\Sigma r + r_e)} \tag{4}$$

K^1 = Thermal resistivity of materials of conductor.
S = Cross-section of conductor.
p = A constant.

For temperatures below 100 deg. cent., p is practically equal to 1; and the solution of (3) therefore assumes the familiar form[7]

$$\log_e \theta = -\mu x + \log_e \theta_1 \tag{5}$$

where θ_1 denotes the temperature rise at $x = 0$.

6. Preston, Theory of Heat, pp. 631-636. A. Winkelman, Handbuch der Physik, III. Wäime, p. 451 (1906)

7. For values of p only slightly greater than 1, it can readily be shown that the solution of (3) may be written in the form

$$\log_e \theta \left\{ 1 - \frac{p-1}{4} \log_e \theta \right\} = -\frac{\mu}{\sqrt{\frac{p+1}{2}}} x + \log_e \theta_1 \left\{ 1 - \frac{p-1}{4} \log_e \theta_1 \right\} \tag{5a}$$

By placing thermocouples in small holes drilled through the insulation at different points, it is therefore possible to determine μ and by noting the temperature on a couple in contact with the covering of the insulation it is further possible to determine the ratio Σr to r_e. The method thus gives, in one experiment, data from which both the thermal resistivity (K) of the particular insulation as actually put on the cable, and the surface resistivity (H) may be determined.

II. Experimental

Lengths of about five feet of each of the cables described below were used in the experiments. A few inches at one end were bared and the conductor surrounded by a heating coil. The heated end was packed in some good heat-insulating material contained in a wooden box, so that no heat would penetrate the cable insulation except through the conductor. Holes were drilled through the insulation into the copper at distances of three or five inches apart, a small mercury globule dropped into the bottom of each hole, and calibrated thermocouples (10-mil diameter calorite-advance) placed in the holes.

Description of Cables Tested. (For meaning of symbols consult Table I.)

Cable A. 500,000 cir. mils. $\nu = 61$ $\delta = 0.0906$, $d = 0.8154$. *Rubber insulation*, $D_1 = 1.003$; cotton braiding impregnated with asphaltum, $D_2 = 1.12$.
$S = 0.393$ $R = 1.793 \times 10^{-6}$

Cable B. 0000 solid conductor, $d = 0.46$. *Varnished cambric insulation*, $D_1 = 0.616$; asbestos and cotton braiding, $D_2 = 1.06$.
$S = 0.166$ $R = 4.16 \times 10^{-6}$

Cable B-1. Same as B; cotton and asbestos covering removed.

Cable C. 250,000 cir. mils. $\nu = 37$, $\delta = 0.0823$, $d = 0.5754$. *Varnished cambric insulation*, $D_1 = 0.952$; lead covering, $D_2 = 1.14$.
$S = 0.196$ $R = 3.582 \times 10^{-6}$

Cable C-1. Same as C. Lead painted dull black.

Cable D. *Three-conductor cable*, each conductor 250,000 cir. mils. *Varnished cambric insulation* on each conductor, $D_1 = 0.70$. Jute and compound between conductors and outside layer of varnished cambric, diameter over three conductors, 1.640. *Varnished cambric insulation*, $D_1 = 1.765$; lead covering, $D_2 = 1.984$.

Cable D-1. Same as D. Lead painted dull black.

Cable E. 250,000 cir. mils, $d = 0.5754$; rubber insulation, $D_1 = 0.825$; lead casing, $D_2 = 0.935$; tape treated with rubber compound, $D_3 = 1.007$; braided with galvanized steel wire and thoroughly painted, $D_4 = 1.07$.

$S = 0.196\ R = 3.582 \times 10^{-6}$

The thermocouples used gave an electromotive force of about 0.04 millivolts per deg. cent. Under the actual experimental conditions a rise of temperature of 1 deg. cent. produced a deflection of 6.4 millimeters on the scale, at one meter. Denoting the deflection by α, it is evident from the proportionality between Θ and α in the range of temperatures used (20-60 deg. cent.) that in equation (**5**) we could substitute α for Θ.

TABLE II.
EXPERIMENTS ON CABLES C AND C-1
Deflection at $x =$

No. of Expt.	2	5	8	11	14	17	20	23	μ
1	438	338	257	203	156	120	91	68	0.0860
	(438)	338	261	202	156	121	93	72	(Calculated)
2	427	320	240	180	138	103	76	55	0.0947
	(427)	320	240	180	135	101	76	57	(Calculated)
3	411	307	225	169	130	96	71	51	0.0958
	(411)	307	230	173	130	97	72	55	(Calculated)
4	420	313	231	174	132	97	71	50	0.0971
	(420)	315	236	177	133	99	74	56	(Calculated)

While theoretically it is only necessary to obtain values of Θ for two different values of x in order to calculate μ, readings were usually taken at five or more different points along the cable. The values of log α were then plotted as ordinates with corresponding values of x as abscissas. From the straight line drawn through all the points (or so as to take in as many points as possible) an average value of μ was then determined.

To check the results, the average value of μ from all the experiments on any one cable was then used to recalculate the deflections on the galvanometer scale corresponding to the different points.

The temperature at the surface was very easily determined in case of lead-covered cables by drilling holes into the lead and

securing an intimate contact between the lead and the couple by means of a mercury globule. In the case of cotton-covered cables, the couple was cemented to the surface by means of Canada balsam and a narrow band of tape.

As an illustration of the results obtained, the Table II gives the observations in four experiments with cables C and C-1. In the last three of these the lead covering was painted dull black.

In experiment 1, the deflections were recalculated from $\mu = 0.086$, in the other experiments the average value from the three experiments was used to recalculate the deflections. When it is considered that a deflection of 6.4 corresponded to a difference of 1 deg. cent., the agreement must be considered quite satisfactory.

TABLE III.

Cable	μ	$\Sigma r + r_e$	W	$r_e W$	Σr	r_e	H	K	Calculated Σr	Calculated r_e
A	0.0765	47	0.0213	0.74	12.2	34.8	122	242	12.6	34.1
B	0.085	90	0.0111	0.40	54	36	120	410	—	—
B–1	0.095	72	0.0139	0.79	15.1	56.9	110	330	18	62
				0.69	22.3	49.9	97	480		
C	0.086	74	0.0135	0.69	23	51	183	290	24	53
C–1	0.096	59.5	0.0168	0.61	23.2	36.3	130	290	24	39
				0.62	22.6	36.9	132	283		
D	0.0652	43	0.0233	0.71	12.4	30.6	191	288	12.9	31
D–1	0.74	33.4	0.0300	0.69	10.3	23.1	144	240	12.9	23
				0.65	11.3	22.1	138	261	12.9	22
E	0.110	45.5	0.022	0.59	18	27.5	91	260	18	32

By means of equation (4), values of $(\Sigma r + r_e)$ were calculated from the values of μ. In accordance with the most recent data on the thermal conductivity of copper[8] I have used the value $K' = 0.108$.

In Table III are tabulated the values of μ, $\Sigma r + r_e$; W; $r_e W$; r_e and Σr. The value of

$$r_e W = \frac{r_e}{\Sigma r + r_e}$$

was obtained from the temperature readings on the couples inside and outside the layer of insulation. From r_e and D_e,

8. Jaeger and Disselhorst, Wiss. Abh. d. Phys. Techn. Reichsanstalt, 3, 269 (1900).

the value of H was determined as indicated in equations (1) and (2). From Σr the average value of K for the different materials composing the insulation was determined in the same manner.

Assuming K for treated tape to be about 270 (Symons) and that the resistivity of the cotton braiding and rubber are approximately equal, we can deduce from the above experiments the following values of K for different materials:

Rubber	250
Varnished cambric (lead-covered cables)	300
" " (cotton " "	400

In view of the influence of slight errors in the experimenta observations on the values of K, only round numbers have been given.

The difference in the thermal resistivities of the lead-covered and cotton-covered varnished cambric insulations, is no doubt due to the presence of air spaces between the insulation and covering in the latter case.

For the surface resistivity H, the numbers deduced from the above experiments are as follows:

H for different surfaces	
Painted steel braided armor	100
Cotton covering	120
Lead, ordinary smooth	190
" painted dull black	140

In the last two columns of Table III are given the values of Σr and r_s calculated by means of these data.

The most striking feature about these results is the effect of painting the lead on its surface resistivity. The fact that Σr remains constant while r_s alone varies as a result of painting the surface is very strikingly brought out by the results recorded in Table III. (Compare C and C-1; D and D-1). That, consequently, the current carrying capacity of the cables is thereby increased is also seen from the carrying capacities given in Table IV as calculated by means of equation (2).

Table IV shows that by painting the single-conductor lead cable, the carrying capacity for $T = 60$ deg. cent, is increased about 11.4 per cent., while in the case of the three-conductor cable the increase is 13.5 per cent. While this is quite in accord with what is known about the laws of surface losses, it is interesting to note that by *painting the lead-covered cable the carrying capacity can be increased as much as* 12 *per cent.*

Note on the Calculation of K for Varnished Cambric Insulation from Σr for Three-Conductor Cable. In comparing the values obtained for Σr in the case of cables C and D and of C-1 and D-1 it was found that the results could be calculated fairly well by assuming that the only effective thermal resistance in the case of three-conductor cables is the sum of the resistance of insulation on one of the conductors together with that of the covering, to which must of course be added the surface resistance.

Thus in the case of Cable D (or D-1),

$$\Sigma r = 300\left(0.365 \log \frac{0.70}{0.5754} + 0.365 \log \frac{1.765}{1.640}\right)$$

$$= 12.9$$

instead of 10.3 to 12.4 as obtained experimentally.

TABLE IV

		i for T =				
Cable	W	60	40	30	20	10
A	0.0213			571	475	342
B	0.0111	365	307	270		
C	0.0135	433	365	321		
C–1	0.0168	482	407	359		
D	0.0233	292	247	218		
D–1	0.0300	332	280	247		
E	0.0220		460			

In other words, the thermal resistance of the jute and compound is neglected, and the effective thermal resistance is that obtained by *assuming each conductor to transmit heat through only that one-third of its surface which is in contact with the covering.*

Apparently the same idea might be extended to twin conductors. The effective resistance would in that case also be that of the insulation around one conductor and that of the covering over both conductors.

Tests on the Carrying Capacity of Cable E. In order to see how accurately the carrying capacity could be calculated from experimental determinations of μ, an actual test was carried out with cable E.

About 40 feet of the cable were stretched out along the floor, being supported about six inches above the latter by means of

blocks at intervals of three feet. The temperature at the copper was determined by means of thermocouples placed in holes drilled through the insulation. The temperature at the surface was also determined by fastening a couple to the steel braided armor in the manner described above. During the heating, readings were taken on one of the couples at intervals of 5 minutes and from time to time observations were taken at other points along the cable to see that the temperature rise was uniform. The second column in Table V gives the temperature rise at different intervals of time while constant current was passing through the cable. The third column gives the excess of temperature above that of the room at different intervals of time after breaking the current.

TABLE V

Time in minutes	Temperature above that of the room	
	On heating	On cooling
0	0	37.0
5	8.3	28.6
10	13.1	22.1
15	18.1	19.0
20	21	14.3
25	25	12.6
30	26.7	10
35	29.0	7.7
40	30.7	6.1
50	32.9	4.3
55	33.3	3.6
65	34.6	2.1
75	35.2	
95	35.6	
125	37.0	

The heating and cooling curves are plotted in Fig. 1. The heating curve indicates that at the stationary state ($t = \infty$) the temperature rise would have been 38 deg. For a temperature rise of 40 deg. the carrying capacity would therefore be

$$450 \sqrt{\frac{40}{38} \times \frac{1}{1.008}} = 460 \text{ amperes}$$

This agrees very well with the result calculated in Table III, and shows that the indirect *method based on the determination of* μ *is quite reliable.*

Temperature of the Surface. The ratio of the external resistance (r_e) to the internal thermal resistance (Σr) of the insulation was determined by noting the temperature of the surface. Corresponding to a temperature rise of 38 deg. cent. at the conductor, the temperature of the surface was 23 deg. cent. above that of the room. This gives a value for $r_e W$ of 0.6 and agrees very well with the result, 0.59, deduced in Table III.

Rates of Heating and Cooling. The smooth curves drawn through the points on the heating and cooling curves are found to satisfy the equations

$$\theta = 38\,(1 - \epsilon^{-0.0425\,t}) \tag{6}$$

and

$$\theta = 37\epsilon^{-0.016\,t} \tag{7}$$

respectively, where θ denotes the excess of temperature above that of the room at the time t (in minutes).

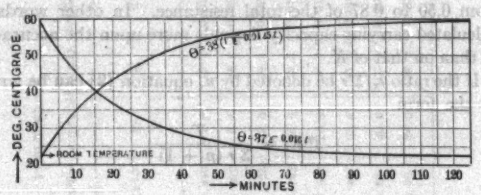


FIG. 1

III. CURRENT-CARRYING CAPACITIES OF RUBBER- AND VARNISHED-CAMBRIC-INSULATED CABLES

In the following section the data determined above have been used to calculate the current-carrying capacities of the various standard types of cables. The method of calculation is that indicated in equations (1) and (2). In Table VI are given the constructional data for rubber-insulated cables together with the calculated values of Σr, r_e, W and i, based upon $K = 250$ and $H = 120$.

Table VII gives similar data for varnished-cambric-insulated cables, braided and leaded. The equations used in the calculations of r and r_e were as follows:

Braided cables $r = 400 \times 0.365 \times \log D/d$

Leaded " $r = 300 \times 0.365 \times \log D_1/d$.

Braided and leaded cables, $r_e = \dfrac{H}{\pi D_2}$

The values of ν, δ and d were obtained from the tables given in *G. E. Bulletin* No. 4787, pages 8 and 9. Data for D, Table VI, were taken from the tables, page 26, while values of D_1 and D_2, Table VII, were taken from the table on page 41 (thickness of insulation based on working pressure of 1000 volts).

On page 56 of the same bulletin are given the current-carrying capacities from which were taken the figures in the last two columns of Table VI and the last column of Table VII.

In all cases a room temperature of 20 deg. cent. has been assumed, and T = rise in temperature above 20 deg. cent.

Degree of Accuracy of Calculated Carrying Capacities

The most important fact brought out in these tables is the *effect of the radiating surface on the carrying capacity of the cable.* Comparing Σr and r_e for the same size of cable, it is seen that the thermal resistance of the surface varies in the different cases from 0.50 to 0.87 of the total resistance. In other words, the calculated carrying capacity depends more upon the accuracy of H than on that of K.

If the ratio $r_e/\Sigma r$ be denoted by n, equation (2) can be written in the form

$$i^2 R_T = \frac{T}{\Sigma r\,(n+1)}$$

Hence, it is readily shown that

$$\frac{\triangle i}{i} = -\frac{\triangle (\Sigma r)}{2\,(n+1)\,(\Sigma r)} \tag{8}$$

$$\frac{\triangle i}{i} = -\frac{-\triangle (r_e)}{2\left(1+\frac{1}{n}\right) r_e} \tag{9}$$

Assuming that on the average $n = 2$, it is seen that a change of 10 per cent, say, in the value of K affects the calculated value of i by no more than 1.6 per cent, whereas a similar change in the value of H, affects the value of i by 3.3 per cent.

Now with regard to the accuracy of the particular values of K and H used in the above calculations, we may assume the limit of error as 15 per cent in the case of K and 10 per cent in the case of H. Consequently the *possible error in the calculated carrying capacities may be estimated at about 2.5 per cent.*

TABLE VI

Carrying capacities of rubber-insulated cables (suspended in air). Single-conductor, single braid.

Size of cable	ν	t	S	d	D	$R \times 10^6$	Zr	r_e	W	i for T =			i according to *G. E. Bull.*	i according to *N. E. Code*
										30°C.	20°C.	10°C.		
2,000,000 cir. mils.	127	0.1255	1.57	1.632	1.99	0.449	7.9	19.2	0.0369	1501	1247	898	1400	1050
1,000,000 " "	61	0.1281	0.786	1.153	1.48	0.897	9.9	25.8	0.0280	925	769	554	900	650
500,000 " "	61	0.0906	0.393	0.8154	1.12	1.793	12.6	34.1	0.0214	572	476	342	550	390
250,000 " "	37	0.0823	0.197	0.5754	0.87	3.582	16.4	49.3	0.0166	356	296	213	320	235
0 B. & S.	19	0.0746	0.083	0.3750	0.63	8.507	20.6	60.7	0.0123	199	166	119	165	124
4	7	0.0773	0.033	0.2319	0.42	21.46	23.6	91.0	0.0087	105	88	63	75	64
6	*Solid*		0.0206	0.1620	0.35	34.21	30.6	109.1	0.0072	76	63	45	50	46
10	*Solid*		0.0082	0.1019	0.24	86.40	34.0	159.2	0.0052	41	34	24	20	24

TABLE VII

Carrying capacities of varnished-cambric-insulated cables (suspended in air). Single-conductor, leaded and braided.

Size of cable	Braided							Leaded								i according to G. E. Bull. $T = 60$
	D	Σr	r_e	W	i for T =			D_1	D_2	Σr	r_e	W	i for T =			
					60°C.	40°C.	30°C.						60°C.	40°C.	30°C.	
2 000,000 cir. mils.	2.14	17.3	17.8	0.0285	1775	1497	1318	1.89	2.14	6.9	28.3	0.0284	1773	1496	1317	1750
1,000,000 " "	1.56	19.2	24.5	0.0229	1126	949	836	1.37	1.56	9.4	38.7	0.0208	1073	904	797	1150
500,000 " "	1.19	24.0	32.1	0.0178	703	592	522	1.00	1.19	9.8	50.8	0.0165	676	570	501	660
250,000 " "	0.95	27.6	40.2	0.0139	438	370	326	0.76	0.95	13.2	63.7	0.0130	425	358	315	390
0 B. & S.	0.66	35.9	57.9	0.0107	250	210	185	0.53	0.66	15.6	91.6	0.0093	233	197	173	195
4 B. & S.	0.45	42.2	84.9	0.0079	135	114	100	0.36	0.45	21.0	134.4	0.0064	122	103	91	92
6 B. & S.	0.40	57.6	95.5	0.0065	97	82	72	0.31	0.40	25.7	151.0	0.0057	91	76	67	60

NOTE: For data on ν, k, d, S and R consult Table VI.

Representation of Carrying Capacities by a General Formula. Melsom and Booth found that they could express the results obtained by them for the current-carrying capacities of rubber- and paper-insulated cables by an empirical equation of the type

$$\frac{i}{S} = c\left(\frac{D}{S}\right)^{N} \tag{10}$$

This may be written in the more convenient form:

$$\log\left(\frac{i}{S}\right) = N \log\left(\frac{D}{S}\right) + B^{*} \tag{11}$$

Where D = outside diameter of cable in inches,
S = cross-section of conductor in square inches,
and i = current in amperes,

they obtained the following values for N and B:

TABLE VIII

Constants for calculating carrying capacities of rubber- and paper-insulated cables according to Melsom and Booth

Type of insulation	N	B for T =		
		11.1 deg.cent.	16.7 deg.cent.	27.7 deg.cent.
Rubber-covered in air.	0.616	2.5611	2.6600	
Rubber-covered in casing.	0.66	2.4900	2.5539	
Lead-covered, paper-insulated.	0.50	2.6325	2.7292	2.8376

It is rather remarkable that the same form of equation expresses the results given in Tables VI and VII pretty closely.

In Fig. 2 the values of $\log\left(\frac{i}{S}\right)$ obtained from Table VI have been plotted as ordinates with corresponding values of $\log\left(\frac{D}{S}\right)$ as abscissas. The results given in Table VII for varnished cambric, cotton covered cables have been plotted in a similar manner in Fig. 3. The slope of the line thus obtained in each

*Logarithms to base 10 are of course meant, except where otherwise indicated.

case gives the exponent N, while B may be determined either graphically or in the usual manner.

The constants obtained for the three types of insulation tested are given in the following table:

TABLE IX

Constants for calculating carrying capacities of rubber- and varnished-cambric-insulated cables, suspended in air.

Type of insulation	N	B for T =				
		60 deg.	40 deg.	30 deg.	20 deg.	10 deg.
Rubber-covered.	0.515			2.93	2.85	2.707
Varnished cambric cotton-covered.	0.545	2.985	2.911	2.856		
Varnished cambric lead covered.	0.525	2.975	2.901	2.846		

Table X indicates the good agreement between the values of i calculated from the above interpolation formulas and the values obtained by the more elaborate calculation given in Tables VI and VII. Denoting the latter by i_1, and those calculated by means of Table IX by i_2, we find that with very few exceptions the two numbers agree to within two per cent.

TABLE X

Values of i_2/i_1

Size of cable	Rubber (T = 30 deg.)	Cambric braided (T = 60 deg.)	Cambric leaded (T = 60 deg.)
2,000,000 cir. mils.	1.007	1.012	0.985
1,000,000 cir. mils.	1.002	0.980	1.050
500,000 cir. mils.	1.003	0.989	0.982
250,000 cir. mils.	1.01	1.022	1.000
0 B. & S.	1.007	0.995	0.996
4 B. & S.	0.983	0.983	1.005
6 B. & S.	0.996	1.030	1.010
10 B. & S.	1.001		

Comparison of Results Obtained with Carrying Capacities According to G. E. Bulletin and N.E. Code. In Tables VI and VII are also given the carrying capacities recommended in the *G. E. Bulletin* and those according to the N. E. Code, 1907. From these figures the curves *AA* and *BB*, Fig. 3, and *CC*, Fig. 4, have been plotted. It must, however, be noted that the figures given in the *G. E. Bulletin* are for the cables drawn in ducts; furthermore, while the thermal resistances in Table VII have been calculated for a thickness of insulation to be used with a pressure not exceeding

1000 volts, the carrying capacities recommended in the *G. E. Bulletin* are intended to be used for pressures not exceeding 3000 volts.

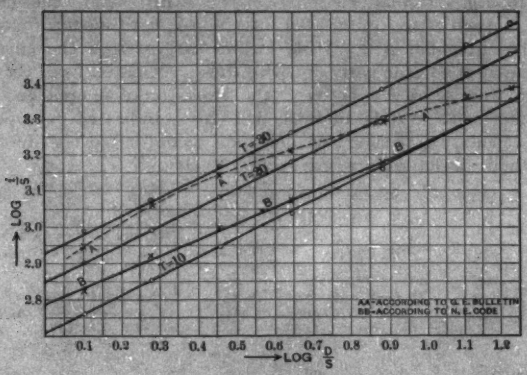


FIG 2

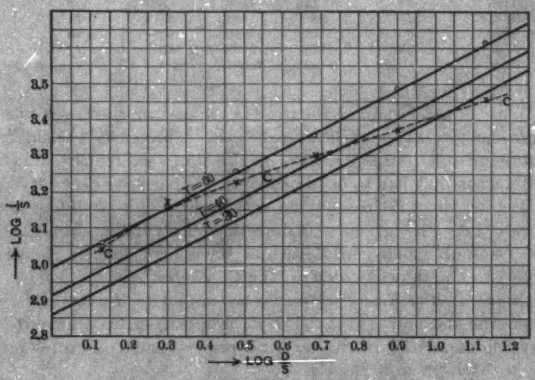


FIG. 3

The calculated carrying capacity is, however, thereby diminished only one or two per cent, because the effect of increased thickness of insulation is almost neutralized by the effect of increased radiating surface.

It will be noticed that the currents recommended by the N. E. Code are evidently based on $T = 15$ deg. for large sizes and $T = 10$ deg. for smaller sizes. On the other hand, the carrying capacities recommended in the *G. E. Bulletin* follow a rather irregular law. While for the larger sizes the currents recommended are nearly equal to those calculated from thermal data, the difference between the two sets of figures becomes greater as the size is diminished. This is indicated even better by calculating the current densities according to the different methods of determining carrying capacity.

TABLE XI

Current density, amperes per sq. in.

Size of cable	Rubber insulation ($T = 30$ deg.)			Varnished cambric insulation $T = 60$ deg.		
	Thermal data	G. E. *Bulletin*	N. E. Code	Thermal data		G. E. *Bulletin*
				Braided	Leaded	
2,000,000 C.M.	956	892	669	1130	1129	1114
1,000,000	1177	1124	827	1432	1366	1463
500,000	1455	1400	992	1788	1720	1680
250,000	1807	1624	1193	2223	2158	1980
0 B. & S.	2397	1988	1494	3011	2807	2349
4 B. & S.	3182	2273	1940	4091	3698	2788
6 B. & S.	3690	2428	2233	4709	4417	2913
10 B. & S.	5000	2439	2927			

While it would thus appear as if for certain purposes the current density on the smaller sizes could be increased considerably, it must also be remembered that the temperature rise is not the only factor that has to be considered. Where the necessity arises of keeping the $i\,R$ drop within certain limits, it would be impossible to use such high current densities with smaller sizes of cables, and no doubt such considerations have been largely effective in regard to the figures given in the *G. E. Bulletin*.

Comparison of Results Obtained with those of Melsom and Booth. From the data in Table VIII it is possible to calculate the carrying capacities of rubber- and paper-insulated cables according to Melsom and Booth.

For rubber-covered cables in air, for $T = 10$ deg.,

$$\log\left(\frac{i}{S}\right) = 0.616 \log \frac{D}{S} + 2.53 \text{ (Melsom and Booth)}$$

$$= 0.515 \log \frac{D}{S} + 2.707 \text{ (Table IX)}$$

For lead-covered cables in air (paper-insulated), for $T = 30$ deg.,

$$\log \frac{i}{S} = 0.50 \log \frac{D}{S} + 2.860 \text{ (Melsom and Booth)}$$

$$= 0.525 \log \frac{D}{S} + 2.846$$

Table XII gives a comparison of the current densities calculated for different sizes of cable according to both sets of equations.

TABLE XII

Size of cable	D/S	Rubber-covered according to		Lead-covered according to	
		Table IX	M. & B.	Table IX	M. & B.
2,000,000 cir. mils.	1.27	575	392	795	816
500,000 " "	2.85	873	646	1216	1222
0 B. & S.	7.59	1445	1180	2032	1995
6 B. & S.	17.00	2193	1941	3105	2985
10 B. & S.	29.3	2897	2716	4130	3917

On the whole, the two sets of equations give results that are within two per cent for lead-covered cables, but for rubber-covered cables the agreement becomes better only in the smaller sizes.

Calculation of Rates of Heating and Cooling and Carrying Capacities under Intermittent Use.

Let q = Rate at which energy is supplied to conductor, in watts per inch length of conductor.

C = Heat capacity of cable per 1 inch length, in watts.

W = Watts transmitted through insulation for 1 deg. difference in temperature, per 1 inch length.

$$\text{Then } q = \frac{C}{60} \frac{d\theta}{dt} + W\theta^* \tag{12}$$

where θ = temperature rise at the conductor at time t, in minutes.

*This equation is only approximately true, but the value of b obtained is probably within 10 per cent of the true result.

Integrating (12),

$$\theta = \frac{q}{W}\{1 - \epsilon^{-bt}\} = T(1 - \epsilon^{-bt}) \tag{13}$$

where $b = 60\ W/C$
and $T = q/W$ = maximum temperature rise.

Hence, it is possible to calculate b, if C and W are known.

Referring to the record of the test on the carrying capacity of cable E, the average value of b determined from heating and cooling curves was found to be 0.044. Since $W = 0.022$, $C = 30$ *watts per* 1 *inch length*.

On the other hand, it is possible to calculate C from the heat capacities of the various materials.

Heat capacities in watts per cubic inch.

Copper	55
Rubber	22.5
Lead	23
Iron (steel)	55

From these data and the thicknesses of the various layers we obtain the value $C = 29$, which is in close agreement with the observed value.

In Table XIII, C has been calculated for several of the rubber-insulated and varnished cambric-insulated cables. From the value of C and that of W (Table VI and VII), b has been determined by means of the relation

$$b = \frac{60\ W}{C}$$

From the equation

$$\frac{\theta}{T} = 1 - \epsilon^{-bt} \tag{13a}$$

it is seen that the heating curves of all sizes of cables can be represented by a generalized curve with the equation

$$\frac{\theta}{T} = 1 - \epsilon^{-x}$$

where the *unit of x* is the time in minutes required for the temperature rise to attain 63.21 per cent of its ultimate value; that is, the *unit of time is* $\frac{1}{b}$ minutes.

Such a generalized heating curve is represented in Fig. 4. The four values of x at which θ is 0.5, 0.75, 0.90 and 0.95, respectively, of its ultimate value have been indicated on the curve. Similarly the value of x for any other value of $\frac{\theta}{T}$ may be determined from the curve. The cooling curve $\frac{\theta}{T} = \epsilon^{-x}$ has also been plotted with the same units.

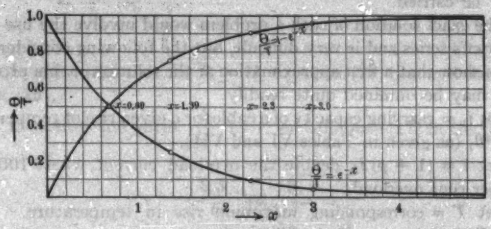


FIG. 4

The use of these curves may be illustrated thus:

If $b = 0.044$, $\frac{1}{b} = 22.73$ minutes. Consequently the intervals of time required for the temperature rise to attain 50, 75 and 90 per cent of its maximum value are 0.69×22.73 (= 16), 1.39×22.73 (= 32) and 2.3×22.73 (= 52) minutes, respectively.

In Table XIII are given the values of t (in minutes) at which the cable would attain 50, 75, 90 and 95 per cent of its maximum temperature rise.

TABLE XIII

Size of cable	C	b	t for $\theta/T =$ 0.5	0.75	0.9	0.95	D_2	$D_2 b$
Rubber-insulated								
2,000,000 cir. mils.	110	0.022	31	63	105	136	2.0	0.044
500,000 " "	32	0.040	17	35	58	75	1.12	0.044
0 B. & S.	9	0.082	8	17	28	37	0.63	0.051
6 B. & S.	2.8	0.15	5	10	15	20	0.35	0.052
Varnished-cambric-insulated.								
2,000,000 cir. mils.	120	0.014	49	99	164	214	2.14	0.030
500,000 " "	35	0.030	23	46	77	100	1.19	0.036
0 B. & S.	10	0.060	12	23	39	50	0.66	0.039
6 B. & S.	3.3	0.11	6	13	21	27	0.40	0.044

As is seen from the last two columns, the rate of heating (or cooling) varies approximately inversely as the outside diameter for rubber-covered cables. This rule does not, however, extend to varnished-cambric-insulated cables.

A much more general problem, however, than that of calculating the rates of heating and cooling of cables is the determination of the carrying capacity under intermittent use, or the calculation of the interval of time during which a definite overload may be carried.

The exact solution of such a problem would involve the use of Fourier's series and is very difficult, but the following considerations show that a first approximation at the solution of this problem may be obtained quite readily.

Let i_1 = carrying capacity of a cable for a given rise of temperature θ_1 (as given in Tables VI and VII).

Let $i = (1 + p)\, i_1$ denote the overload current, where $100\, p$ = per cent overload.

Let T = corresponding maximum rise in temperature.

From equation (**2**) it follows that

$$i_1^2\, R\, (1 + 0.004\, \theta_1) = W\, \theta_1$$
$$i^2\, R\, (1 + 0.004\, T) = W\, T$$

Consequently

$$\frac{\theta_1}{T} = \frac{1 + 0.004}{\dfrac{i^2}{i_1^2}} - 0.004\, \theta_1 \tag{14}$$

and the interval of time, t_1, during which the overload may be applied, is given by the relation

$$t = \frac{2.3}{b} \log \frac{T}{T - \theta_1} \tag{15}$$

Thus by combining equations (**14**) and (**15**) it is possible to calculate t for given values of θ_1 and i/i_1, if b is known.

Now consider the case in which the cable has an initial load of i_0 amperes before the overload current is applied. Assuming that this initial current is over 50 per cent of the normal carrying capacity (i_1) and that it has been passing until the stationary state of temperature distribution has been attained, the relative temperature increments at the stationary state without overload (θ_0) and with overload (θ_1) are given by

$$\frac{\theta_0}{\theta_1} = \frac{i_0^2}{i_1^2} \tag{16}$$

When the overload current is applied, the maximum rise of temperature above θ_0 will be $T-\theta_0$, and the interval of time taken to attain the temperature rise T will be given by the equation

$$t = \frac{2.3}{b} \log \frac{T-\theta_0}{(T-\theta_0)-(\theta_1-\theta_0)} = \frac{2.3}{b} \log \frac{T-\theta_0}{T-\theta_1}$$

$$= \frac{2.3}{b} \log \frac{\dfrac{T}{\theta_1} - \dfrac{\theta_0}{\theta_1}}{\dfrac{T}{\theta_1} - 1} \qquad (17)$$

It is evident that for $\theta_0 = O$, equation (**17**) becomes the same as (**15**).

Denoting the ratio $\frac{i_0}{i_1}$ by r, we can unite (**17**) in the form:

$$t = \frac{2.3}{b} \log \frac{\dfrac{T}{\theta_1} - r^2}{\dfrac{T}{\theta_1} - 1} \qquad (17a)$$

Now the value of the expression

$$2.3 \log \frac{\dfrac{T}{\theta_1} - r^2}{\dfrac{T}{\theta_1} - 1} = \phi$$

will depend only upon the three variables p, r, and θ. That is, for a given value of θ_1, the value of t is proportional to ϕ and is absolutely independent of the dimensions of the cable. The proportionality constant $\frac{1}{b}$ is the only quantity which depends upon the size of the cable. Its value may be obtained from Table XIII above.

TABLE A. $\theta_1 = 30$

t = interval time for which overload may be carried.

$= \frac{1}{b}\phi$

$100\,p$ = per cent overload; $r = i_0$/normal carrying capacity for $\theta = 30$ deg.

r	ϕ for p					
	0.10	0.20	0.30	0.50	0.75	1.00
0.	1.64	1.064	0.788	0.474	0.281	0.175
0.50	1.41	0.894	0.637	0.375	0.216	0.133
0.6	1.30	0.801	0.566	0.329	0.189	0.115
0.7	1.14	0.685	0.474	0.270	0.154	0.092
0.8	0.914	0.525	0.356	0.198	0.110	0.067
0.9	0.585	0.311	0.202	0.108	0.057	0.035

In Table A, the values of the expression ϕ have been tabulated for $\theta_1 = 30$ and different values of r and p.

The use of this table may be illustrated by the following example.

It is required to determine the value of t for a 2,000,000-cir. mil rubber-insulated cable carrying 60 per cent of its normal current when an overload of 30 per cent is applied.

From the table, it is found that for $r = 0.6$ and $p = 0.3$, $\phi = 0.566$. According to Table XIII, $b = 0.014$. Hence $t = \frac{0.566}{0.014} = 40.4$ minutes. If the cable were not carrying any current initially, it could stand an overload of 30 per cent for $\frac{0.788}{0.014} = 56.2$ minutes.

Tables B and C contain similar data for $\theta = 40$ and $\theta = 60$.

TABLE B. $\theta = 40$

r	ϕ for $p =$					
	0.10	0.20	0.30	0.50	0.75	1.00
0.	1.61	1.03	0.746	0.440	0.246	0.138
0.5	1.38	0.865	0.605	0.348	0.191	0.092
0.6	1.27	0.775	0.536	0.302	0.163	0.078
0.7	1.108	0.660	0.449	0.246	0.131	0.060
0.8	0.891	0.505	0.336	0.182	0.097	0.039
0.9	0.564	0.30	0.191	0.099	0.051	0.012

TABLE C. $\theta = 60$.

r	0.10	0.20	0.30	0.50	0.75	1.00
0.	1.54	0.975	0.680	0.373	0.177	0.072
0.5	1.32	0.805	0.550	0.292	0.138	0.053
0.6	1.20	0.720	0.485	0.253	0.117	0.046
0.7	1.05	0.608	0.405	0.207	0.088	0.037
0.8	0.834	0.465	0.302	0.154	0.058	0.025
0.9	0.528	0.274	0.168	0.080	0.030	0.014

These data may be plotted in the form of curves giving ϕ as ordinates and p as abscissas. By the use of these curves and tables of b it ought therefore to be possible to calculate approximately the interval of time during which any definite overload may be carried.

Summary

The current-carrying capacity of an insulated cable may be calculated from data on the thermal resistivity of the insulation and of the surface. It has been shown that these data may be obtained for any type of insulation from experiments on the cable itself by applying a well-known method for determing heat conductivities.

As a result of experiments on different types of cable insulation, the following values have been obtained for the thermal resistivities (deg. cent. per watt per inch):

Rubber and cotton braid cover	250
Varnished cambric and cotton braid cover	400
" " (lead-covered cables)	300

For the surface resistivities the following values were obtained (deg. cent. per watt per square inch).

Painted steel braided armor	100
Cotton covering	120
Lead, ordinary	190
" painted dull black	140

These data (which are in agreement with those obtained by other investigators) have been used to calculate the carrying capacities of standard rubber- and varnished-cambric-insulated cables suspended in air. It has been shown that over the range of sizes, No. 10 B. & S. to 2,000,000 cir. mils, the current density (i/s) and the ratio of the outside diameter (D) to the cross-section of the conductor (S) are connected by an equation of the form

$$\log\left(\frac{i}{S}\right) = N \log\left(\frac{D}{S}\right) + B$$

where N is a constant for any type of insulation and B depends upon the temperature rise.

The effect of the surface thermal resistance on the carrying capacity has been shown to be much greater, in general, than that of the internal thermal resistance. The magnitude of the surface losses is thus of great importance in determining the current-carrying capacities of insulated cables.

An approximate method has been worked out for calculating the rates of heating and cooling of insulated cables from the thermal resistances and heat capacities of the materials that enter into the construction of the cables. Furthermore, the application has been indicated to the determination of carrying capacities under intermittent use.

In conclusion the author desires to express his appreciation to Dr. I. Langmuir and Mr. W. E. Robinson for their active interest during the progress of the investigation.

GROUP I PAPERS

(Pages 153 to 357)

HEATING, HEAT MEASUREMENTS, RATING BY HEAT

(a) MOVING MACHINERY

Notes on Internal Heating of Stator Coils, by R. B. Williamson.

Measurement of Temperature in Rotating Electric Machines, by L. W. Chubb, E. J. Chute, and O. W. A. Oetting.

Method of Determining Temperature of A-C. Generators and Motors and Room Temperature, by H. G. Reist and T. S. Eden.

Thermocouples and Resistance Coils for the Determination of Local Temperatures in Electrical Machines, by J. A. Capp and L. T. Robinson.

(b) TRANSFORMERS

Methods of Determining Temperature of Transformers and of Cooling Medium, by S. E. Johannesen and G. W. Wade.

Methods of Determining Temperature of Transformers, by W. M. McConahey and C. Fortescue.

Correction of Transformer Temperatures for Variation in Room Temperature, taking into Account both Copper and Iron Losses, by C. Fortescue.

(c) TEMPERATURE CORRECTION

The Temperature Rise of Stationary Induction Apparatus, by J. J. Frank and W. O. Dwyer.

Effect of Room Temperature on Temperature Rise of Motors and Generators, by M. W. Day and R. A. Beekman.

Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus, by C. E. Skinner, L. W. Chubb and Phillips Thomas.

A Laboratory Investigation of Temperature Rise as a Function of Atmospheric Conditions, by C. B. Blanchard and C. T. Anderson.

Laws of Heat Transmission in Electrical Machinery, by Irving Langmuir.

(d) CABLE HEATING

Current Rating of Electric Cables, by R. W. Atkinson and H. W. Fisher.

The Heating of Cables Carrying Current, by S. Dushman.

DISCUSSION ON GROUP I PAPERS (HEATING, HEAT MEASUREMENTS, RATING BY HEAT), NEW YORK, FEBRUARY 26, 1913.

Comfort A. Adams: There is one question I would like to ask of Dr. Dushman, concerning Dr. Langmuir's paper. When Dr. Langmuir first published his work on convection, I happened to be interested in the subject, and put the material into such shape that I could use it easily, but as the theory was only checked by tests on very small wires, I am in doubt as to the validity of the method when applied to large wires or to plane surfaces. I should like to know how far it is safe to go in this direction.

S. Dushman: For a plane surface the thickness of the film is about 0.4 cm., and that will hold practically down to 500,000 cir. mils cable. Below that, the thickness of the film varies with the diameter of the cable, and a table is given.

Comfort A. Adams: Is that the same information as given in the paper which was published in the *Physical Review?*

S. Dushman: I do not think so.

William F. Dawson: I would ask Dr. Dushman and Dr. Langmuir if they have investigated the specific heats of the various insulating materials. We have many data in respect to the thermal resistivity, but glancing through the papers I see no mention of the specific heat of the insulating materials. The specific heat of the various metals is fairly well known, but we do not seem to have available the specific heat of the insulating materials, and that certainly is very important in determining the rapidity with which various conductors will increase in temperature.

I have made some investigations in respect to crane motor ratings, and found that, roughly, the thermal capacity could be assumed at some three to four times the thermal capacity of the copper, but, of course, that is entirely empirical and probably not very accurate. I believe it was Mr. E. H. Rayner who made the investigation at the National Physical Laboratory in 1905 for the English Standards Committee who made the broad statement that the specific heat of insulation material was six times that of copper, but I imagine that is only an approximation.

Leo Schuler: When the International Electrotechnical Commission held its meeting in Zurich in January, the experiments made in this country with regard to the influence of room temperature on the heating of electrical machinery were brought to our attention by your American representative, Mr. Mailloux, who is here present. At that time Mr. Mailloux was under the impression that the influence of air temperature would be very much higher than has been represented in the papers. As we understood from Mr. Mailloux, your experiments have shown that a machine would be heated at a lower temperature so much more than at a higher temperature that the final temperature

attained by a machine would be practically the same, within certain limits, whether the air temperature is high or low.

C. O. Mailloux: That is what I said.

Leo Schuler: Between the limits of 25 deg. cent. and 35 deg. cent. air temperature, the final temperature would be practically the same. However, as far as I can see now, this is certainly not the case. If it had been the case, it would certainly be quite revolutionary compared with the former ideas we had on that subject.

The members of the Committee in Zurich were also of the opinion that it would be quite revolutionary, and that therefore we should drop all discussion on the subject of air temperature. Now, I must say that this is the most important question which I thought would be discussed here, and I should like to have some further information from the gentlemen who made the investigations in regard to the practical results they think their investigations will have on the Standardization Rules which are now to be adopted.

As far as I have seen from the papers, it is advised to leave a correction for air temperature out of the Standardization Rules, and simply stick to the present practise, at least to our present German practise, and simply add the air temperature to the rise and do nothing else.

There is another question: In the paper by Mr. Skinner allusion is made to the "fog-laden air," but there is not much said about that subject. Am I to understand that experiments have been made with fog-laden air and that the cooling of fog-laden air is much higher than ordinary air; and if this is the case, is there any prospect of a practical application of this method? One would think, of course, that the fog-laden air would very soon destroy the insulation by exposing it to the moisture, but I have seen a report in a German paper that in America experiments are being made to use fog-laden air for the more effective cooling of electrical machinery. Perhaps you will give me some information on that.

M. W. Day: With regard to the total temperature obtained under different room temperatures, the question was raised at one time whether possibly in a cold room the motor would rise to a point nearly as hot as in a hot room, but that is far from being the case. The fact that we wished to bring out was, that in a great majority of these cases the temperature rise in a hot room was less than it was in a cold room, but not enough less to make the total temperature the same. Take the case which is shown in Fig. 7, where one machine is run at 47 deg. cent. and the other at 24.5 deg. cent., the temperature at the commutating spool has 20 deg. rise in the hot room and 22 deg. rise in the cold room. That is a semi-enclosed motor. Now, with the open motor without fan shown in Fig. 4, in one or two cases the reverse of this rule holds true, but, take for instance, the shunt field by thermometer; in one test it shows 32 deg. and in

other tests about 33.5 deg., a very small difference, but still enough to be considered when we come very close to meeting specifications.

Turning back to Fig. 1, where the motor is totally enclosed, there is a greater difference. Take the case of the armature where the room temperature was 4.5 deg., the rise of the armature was 41 deg., and where the room temperature was 25 deg., the armature rose about 35 deg. There is 6 deg. difference in temperature rise, with about 20 deg. difference in the room temperature. About the last of the year we sent a copy of this paper to Mr. Mailloux, so that it might be considered at the meeting of the International Electrotechnical Commission in Zurich.

H. M. Hobart: I had charge at one time of some experiments in fog-laden air. The results of the investigations were valuable. I am not prepared to disclose the results but I will state my opinion that fog-laden air will afford a commercially valuable means of cooling machinery. When we have learned to take advantage of a very great number of little points, which are necessary to success, there will be a field for it.

Leo Schuler: I ask whether it is looked upon as a practical question.

H. M. Hobart: I should be disposed to recommend going much further with it, at some time when other things do not stand in the way.

C. O. Mailloux: I would like to make clear the attitude of the delegate from America to the International Electrotechnical Commission, which I do not think was made clear by my colleague, Mr. Schuler. At the time of my departure for Zurich, there were only two of the papers presented here today which were ready, namely the one by Day and Beekman and the one by Steinmetz and Lamme. These papers revealed such radical tendencies and promised revelations of such an important character that I felt it incumbent upon me to warn the Special Committee on Rating at Zurich, when it assembled to discuss the question of rating, not to go too fast in discussing the question of ambient temperature. Feeling that the Standards Committee had a great deal more ammunition up its sleeve, to use a figurative expression, I suggested that discussion might well and profitably be postponed by the International Electrotechnical Commission until after the Midwinter Convention had been held, or until after the papers which had been promised us were thoroughly discussed; but the Committee did not coincide with me. They did not seemingly believe the Americans were quite as wise as I intimated, and they were skeptical in regard to the value of the papers and their discussion. However, by way of protest, I requested the privilege of abstaining from any vote or participating in any formal action; and there was inserted in the Proceedings a note to the effect that the American delegate abstained from voting on this question, feeling that there would

soon be made public in America the results of important researches which would call for very radical modifications of the rules. That is the way the record stands today. The position I took was that any action which the Commission took at Zurich would necessarily be subject to revision and would have to undergo revision of a more or less radical character, after the results of this Convention, including the papers and the discussion, had become public.

Charles P. Steinmetz: Regarding the result, that the temperature rise at higher room temperature is less, I would say that the result is not unexpected, but is what should be expected from the radiation laws. We should expect from the radiation laws that the higher the room temperature the lower is the temperature rise at the same energy dissipation. Unexpected was the result of the single set of experiments which led to the rule previously formulated, which was introduced in the Standardization Rules away back in the last century, when the experiments were first made. The results were introduced into the rules, as they were the only evidence available at that time. Like many other things, these data were put in as the best information available, hoping that the establishment of that rule would lead investigators to study it and give us more exact information. Unfortunately, this hope was not realized until the investigations which are being published today.

W. A. Durgin: Today's discussion of permissible insulation temperatures has emphasized the importance of obtaining reliable means of getting at hot spot temperatures, and as the first group of papers is particularly concerned with such means, it seems that each should receive careful consideration. The central station company with which I am connected desires to place itself on record as being in favor of ascertaining the temperature of large unit windings by exploring coils.

These coils, according to one of the papers, are rather fragile, expensive, difficult to install and require precise measurement. Our experience is quite the reverse. First, as to fragility, we have installed a total of 120 coils in ten turbo-generators, ranging in size from 8 to 20 megawatts. Fourteen of these coils, or 12 per cent, have been damaged and the remainder have been in service from one to 4½ years, the average age of all coils being 2½ years. Some of these are installed between armature coils, some between coil and iron and some on end turns. The expense is negligible, the coils being wound of No. 30 double cotton covered wire in our own laboratory and usually consisting of a single layer some 3 feet long and 1 inch wide. The difficulty of installation will be easily met if you use the thermometer or armature resistance method of following operating temperatures as opportunity will be presented at the time of rewinding your machines. The precision of measurement required is at most merely that of a Wheatstone bridge, while there are at present on the market indicating instruments which may be permanently connected to the coils to give the operator direct temperature readings.

The value of these coils has been greater than we first expected, since they supply a ready means of following the temperature of the machine continuously, thus checking the condition of the ventilating ducts. The operating department has come to depend on our periodic heat tests for necessary information as to when to remove a field, clean the stator, and put the entire unit in first-class condition.

We appreciate, of course, that any exploring coil may not and probably will not give the hottest spot, but it does give a temperature which is strictly related to that of the conductor and this temperature is so much higher than that shown by either the mean resistance or temperature method that as yet we have not been able to get the manufacturers to admit its applicability in determining the rating of a machine.

For all these reasons, therefore, we wish to urge that in reformulating the Standardization Rules the temperature coil method be given very serious consideration, and if possible, presented in conjunction with some average temperature gradients for the various classes of insulation whereby we may determine the temperature of conductor corresponding to the temperature coil indications.

B. G. Lamme: I would like to say something in connection with what the last speaker stated. Last month I presented a paper before the Institute on the subject of turbo-generators, and in that I called attention to the fact that, in large turbo-generators, the temperature drop from the hottest part to those parts which were accessible to measuring instruments, was often excessive; that is, there might be rises of 80 deg. in the slot and 40 deg. or 50 deg. in the end windings. That is a class of machinery in which the temperature drop is liable to be excessive and no thermometer or resistance measurement is going to give indications which are worth anything unless you know approximately the internal drops. In such apparatus thermocouples or exploring coils give a much better approximation to the true temperatures. Such devices do not give the hottest temperatures, but they locate the hot parts and give an approximation of temperature at those points. In certain classes of machinery where internal temperature drops are liable to be very high, measuring devices of that sort are advisable.

M. E. Leeds: As the importance of the measurement of hot-spot temperatures is generally admitted and the two methods of making these measurements which seem to give the best results are by means of thermocouples and exploring coils or resistance thermometers, it would seem worth while to consider the relative advantages of these two methods, which may be summarized as follows:

The thermocouples have the advantage of small size and convenience for insertion, low cost, and small likelihood of deterioration. They have the disadvantage that the forces available

for measurement are very small, being only thirty to fifty millivolts per degree, and require unusually sensitive and relatively expensive apparatus to measure them, and that it is necessary to make a cold-end correction which is such that the scale of the indicator does not read temperatures directly.

Resistance thermometers have the advantage that the forces available for measurement are relatively large, and robust indicating apparatus having moving parts and general construction the same as ordinary moving-coil switchboard instruments with an open easily read scale, may be used; no correction of any kind is necessary and the scale of the indicator reads temperatures directly. They have the disadvantage of greater first cost when calibrated to be direct-reading and constructed so as to insure permanent reliability.

In the case of the testing laboratory of the manufacturing plant where temperatures are to be measured at a very large number of points and where laboratory assistants may be trained to use the more delicate apparatus and make the necessary corrections, it is quite possible that thermocouples will be more economical in spite of the large expense of the reading devices.

In the case of operators of machines where the number of points to be measured is small, the situation is a different one, and the resistance thermometer seems to have decided advantages in that the temperature may be read directly from a robust instrument like other switchboard instruments without special attention, manipulation or corrections of any kind. The higher cost of the parts that go into the machine is to a very large extent offset by the lower cost of the indicating instrument. Should the service require it, the forces available from a resistance thermometer are large enough to operate a simple form of recording instrument with a commutating device which would automatically record in succession the temperature of the various parts of the machine.

I notice a slight mistake in the paper by Chubb, Chute and Oetting, apparently due to an oversight, in the statement that the exploring coils or resistance thermometers must be calibrated for the particular length of lead with which they are furnished. This is not the case for either three- or four-lead construction. The only object in having three or four leads is to compensate for the lead wires, and this compensation is rigid, and is quite independent of the length of the leads.

In the paper by Capp and Robinson is the statement: "The practical value of resistance thermometers for high temperatures is doubtful. Base metal couples are permanently changed in resistance by continued use."

The value of this statement depends on the definition of high temperatures, which is not given. There is a very considerable amount of data now available to show that properly constructed resistance thermometers of nickel wire do not permanently change their resistance when used at temperatures under 250 deg. cent.

L. W. Chubb: In answer to Dr. Leed's criticism on the relative merits of the thermocouple and the resistance coil, let me say that the greater sensibility of the bridge method in measuring with the resistance coil does not justify its use when other errors of great magnitude and of unknown quantity may creep into the results. For instance, resistance coils, consisting of very fine nickel wire, are very easily broken, when being installed in the machine. Also if you are to use such exploring coils to measure the hot spot, you must put them where there is a magnetic field, and it is well known that the resistance of nickel is not the same in a magnetic field as it is without the field.

Recent tests with such exploring coils put in the air gap of a turbo showed 2 deg. cent. jump when the turbo was excited. This was not an inductive kick, but a change in the resistance of the coil.

The thermocouple can be put right where you want it, and quick and more accurate readings of the hot spot can be taken. There are no errors of leads and it is not subject to magnetic fields in the slot of the machine. The use of the potentiometer is advocated when using a thermocouple. Portable, self-contained instruments can be had at a reasonable price and they are sufficiently sensitive to read to a small fraction of 1 deg. cent.

L. T. Robinson: I favor a resistance thermometer over the thermocouple for very obvious reasons; it is an easier thing to handle, and I think when you tack a potentiometer on to anything it is hardly a commercial device. It is a fine thing for research work, but I do not think they would want a thing like that in a central station. I do not see anything in this nickel coil. There is no necessity for it. I see no reason why copper winding is not perfectly satisfactory. Possibly it may be true that nickel has a larger temperature coefficient, it also has a larger resistivity, and that means a coarser wire, and you can in that way build up quite an argument, but, nevertheless, the fact remains that you can make perfectly satisfactory copper coils, that all the cost that goes into them is the labor of making the coil and putting it in. The real trouble is to get the thing in where you want it, without doing some damage to the machine, and to be able to find the ends after you have it there, and it has been there a while. It is quite a problem. It is introducing one class of work, that is, instrument work, into an entirely different class of apparatus, and the people who are familiar with preparing and insulating windings, etc., have not the facility and the fingers to handle the small temperature coil, and they first have to learn how to handle it, before it will be a real commercial success.

R. F. Schuchardt: It is somewhat astonishing to hear a discussion of exploring coils made of nickel or platinum, when copper coils are so simple and successful.

In the installations Mr. Durgin referred to, where we have

90 per cent of the coils installed still in service, we made them of double cotton covered No. 30 copper wire, winding the coil non-inductively and flat with a thickness of a single conductor. We placed them between the armature coil and the wooden wedge, and in a single generator we installed a dozen or more coils in various locations, so that if we lost one or two because of broken connections we still had enough to get satisfactory readings.

There is another point in connection with the use of exploring coils, in generators particularly, which is of great importance. With such coils installed, we can easily put an indicating device on the machine which will tell us the temperature at the point of measurement, which should be as near as we are able to get it to the probable hottest part.

I would like to make this suggestion: That, while, as stated, it is not the function of the Institute to tell manufacturers how to get results, we can very properly recommend to them that, as they put an oil gage on bearings to indicate when the oil level gets below the safe limit, they ought also to attach a temperature indicating device so the operator can readily know when the safe limit of load has been reached.

Elmer I. Chute: The method suggested in Messrs. Reist and Eden's paper, of artificially creating a lag in the thermometers responsible for the measurement of the room temperature, somewhat corresponding to the natural lag in the apparatus under test, has much to commend it. Constant conditions as regards surrounding air in tests on rotating apparatus are much to be desired, but are seldom attained. Under varying air conditions, especially in tests on larger machines, some such device should facilitate the obtaining of more consistent and accurate temperature rises.

The method of covering thermometers, when temperatures are to be taken while running, is without doubt the most important feature in connection with their use for this purpose. On this account, the first table given in this article should be of especial interest to all those concerned in the testing of rotating apparatus. The results here given were, in certain respects, so foreign to the experience of the present speaker, based on comparative tests previously taken on various types of machines, that additional tests were undertaken to determine if possible wherein the discrepancy lay. This discrepancy consisted chiefly in results given in this table for temperatures obtained with a covering of putty for thermometers as compared with a covering of felt in the shape of a small thin pad.

Tests as outlined by the authors of this paper were made and were thoroughly confirmed, that is, the thermometers protected by the putty gave from 5 to 8 deg. in 80 higher than those covered by the felt, and checked within ½ deg. of the true temperature. The true temperature was determined from the average of a number of readings taken around the coverings by a small quick-

acting thermocouple that had been especially checked for the occasion.

It was thought that some of the discrepancy may have been due to the felt pads being affected by the excessive humidity of the surrounding air caused by the proximity of the boiling water, so the same test was repeated with electrically heated grids furnishing the required temperature. In this test at 90 deg. cent. the two methods checked within 3 deg. of each other; the one covered with the putty still giving the higher temperature.

TABLE I

Test No.	Rating of machines in kv-a.	Speed	Temperatures in deg. cent.				Part measured
			Thermometer covered with putty	Thermocouple	Thermometer covered with felt	Thermocouple	
1	150	1200	51	55.7	53	54.5	Core
2	1000	600	61	65.3	68	68.4	Core
3	1000	300	47.8	51.2	52.5	52.1	Core
4	1000	300	51	55.7	53	54.2	Core
5	1000	300	49	50	52	53	After shut down
6	125	300	38.5	39.9	38	38.2	Coil
7	580	750	45.3	49.3	50	49.9	Coil
8	580	750	51	52	50.5	49.9	Core
9	90	560	41	41	42	43	Coil
10	90	560	47	49	43.5	44	Core
11	400	120	28	29.5	32.5	31	Coil
12	400	120	31	32	33	32	Coil
13	400	120	46	46	47	47	Core
14	400	120	47.5	47	46.5	47	Core
15	2000	600	53	54	32	30.5	Coil
16	2000	600	33	37	37	37	Coil
17	2000	600	55	58	56	57	Core
18	75	277	33.5	34.5	33.5	32.8	Coil
19	75	277	37	37	35.5	36	Coil
20	75	277	53	54.7	54	54.2	Core

Tests were next conducted on machines themselves in actual operation. These tests were quite numerous. Table I gives a few of the results obtained.

Thermometers covered with each material were placed in corresponding conditions and the true temperature obtained in each case by exploring around the covering or pad with the thermocouple previously mentioned.

The experiments so far conducted indicate that the discrepancy is chiefly due to the amount of air passing over the coverings. The heat being readily transmitted through the covering of putty enables it to be carried off rapidly, while in the case of the

felt there is considerable temperature gradient through the material.

It may be stated that after shut-down the temperature equalizes to some extent, although the thermometers covered with the putty seldom reach the maximum registered by those covered with the pads.

The absence of all mess and the facility with which the felt pad may be adapted to almost any location on either windings or laminations are strong points in its favor, but the obtaining of temperature closely approximating the true temperature is the vital point to be considered.

Charles P. Steinmetz: The exploring coil or thermocouple is very valuable in certain classes of machines, that is, high-voltage, high-power generators, while in other machines it is not applicable. The exploring coil or thermocouple has, however, two disadvantages: First, in those machines which have one coil per armature slot, it does not show the hottest spot, and if located between the coil and iron, it shows the temperature outside of the insulation, which may be much nearer to the iron temperature than to the copper temperature. If located between the coil and wedge, it shows a temperature the significance of which it is practicably impossible to interpret. Only where there are two coils per slot, and the exploring coil is located between the two coils, then it comes nearer to the copper temperature, but may be higher or lower. If, in addition to the results shown by the exploring coil, the heat resistivity of the insulation is known, you can calculate the copper temperature from the indication of the exploring coil and the flow of heat through the insulation, provided we know the flow of heat—from the copper to the rest of the machine. This, however, we do not know. We could only know this, where the entire heat energy flows transversely through the insulation. In such cases we can correctly interpret the results indicated by the exploring coil. But where a large part flows lengthwise, then the exploring coil temperature has no simple relation to the copper temperature. The exploring coil is mainly valuable, as Mr. Schuchardt pointed out, as an indicating device giving the operating engineer some notion of the temperature condition of the machine, at any moment. But it does not give us the much-desired information where the hot spot is and how hot it is.

Leo Schuler: I think it would be a great drawback if you came to the conclusion to prescribe in the Standardization Rules the adoption of a thermocouple or resistance coil, because, as Dr. Steinmetz pointed out, you will probably not be able to fix that coil at the hottest point. I might mention an experience I had some time ago on a 5000-kv-a. turbo-generator. It was prescribed by the specification that the temperature of the hottest spot should be measured. One would expect the hottest spot on such a machine to be the center of the stator coil in the middle of the machine, and we therefore put a thermo-

couple at that point. As a matter of fact, the temperature measured by that thermocouple was 10 deg. lower than the temperature measured by the total resistance of the coil. As a matter of fact, it was a cold spot.

This was easily understood later; the end windings of the machine were heavily wrapped with insulating tape outside and the dissipation of heat was very bad there, and when measuring by a thermometer at the end windings you got a much higher temperature than at the so-called hot spots. If you really say in your new rules that the manufacturer should place a thermocouple or something of that kind on the hottest spot of the machine, then I think the manufacturer would be very wise to find out the correct place for that coil.

A. E. Kennelly: I want to say that I noticed, in these papers that we are discussing, that there are various inferred absolute temperatures of copper, from 233.3 to 238. The most recent value given by the action of the Bureau of Standards and which, I understand, is likely to be accepted by the International Electrotechnical Commission, is 234.5. That is an easy number to remember.

Another point is that the unit of thermal resistivity is given in some of the papers as watts per deg. cent. per cu. in. That is generally admitted to be inaccurate. It should be watts-inches per degree cent.; or watts per deg. cent. in a cubic inch. That is, it should multiply by the inch and not divide by the cubic inch. This is important, when transferring to metric measure.

Another point is that one of these papers brought out to us the fact that at lower room temperatures, the temperature increase is greater than at higher room temperatures, which seems at first very surprising. We are accustomed to think of the heating effect of constant current strength in a coil of copper wire at different temperatures. Here the I^2R loss increases with the room temperature and the temperature elevation may be expected to increase also with the room temperature.

With constant power input, however, or with constant impressed difference of potential, the case would be different—here we have a higher temperature reached with respect to surrounding objects, and the radiated loss increases as the fourth power of the absolute temperature. I think that explains the fact, taken in conjunction with another important principle, that part of the core losses diminish as the temperature goes up. The eddy-current losses diminish as the temperature goes up, and therefore there is less loss at a higher temperature than at a lower temperature.

B. G. Lamme: I like the way the discussion is going this evening, because it is so nearly in line with the recommendations in the paper on temperature and electrical insulation. In that paper, we recommended certain temperature limits obtained by conventional methods of measurement, plus an internal drop

which cannot be measured accurately. If, in the proposed conventional methods, thermocouples or resistance coils be included as one class of thermometer measurements, then our recommendations for determination of temperature by conventional methods of thermometer and resistance will hold for all kinds of apparatus. In those cases which were beyond the limits of the mercury or fluid thermometer the thermocouple or resistance coil could be used instead. The method proposed remains the same, whatever the method of measurement. This morning apparently there was considerable disagreement regarding our proposed method of getting at the hot spots. This evening, it is apparently the opinion that if we use a thermocouple or exploring coil in a high-voltage armature winding, and thus obtain the nearest we can to the high temperature and make a reasonable allowance for the internal drop, the result will be what is wanted;—but that is just what we proposed this morning.

I wish to take exception to one statement made by Mr. Robinson. I would limit the use of exploring coils or thermocouples to stationary apparatus, for in rotating apparatus experience shows that such devices are not satisfactory during operation, as some moving contact must be interposed to obtain readings when in operation. These are not very satisfactory, according to my experience. Moreover, rotating armatures represent a great proportion of the total apparatus on which temperature measurements are to be made, as this covers all direct-current armatures. Therefore, the thermocouple or exploring coil should be limited to stationary apparatus, or to moving apparatus only after shut-down.

L. T. Robinson: I am willing to accept Mr. Lamme's limitation for rotating members. It is just so.

James Burke: We have been considering various methods of determining hot spots. I would suggest one other method—the method of mind reading hot spots. In applying the mind reading method, if we find by thermometer we have 40 deg. temperature increase, and by resistance of the winding, 50 deg., then we can say by mind reading that the probable hot spot is 60 deg. If by thermometer we have 40, and by resistance 55, we may conclude that the hot spot is 70 deg.; if by the thermometer we have 40 and by resistance 60, we may conclude the hot spot is 80 deg. It is an approximate treatment of it, but perhaps comes near the true hot spot temperature. It does not tell us where the hot spot is and it does not tell the exact truth, but it approaches it.

C. P. Steinmetz: How about when the thermometer reading shows a higher temperature than the resistance method?

James Burke: Then we can conclude that the thermometer reading is the truth.

Robert Lundell: I wish to refer to the increase in temperature of machinery in hot and cold rooms. I cannot help thinking

that the machines which were tested were rather inefficient at the low loads, that is to say, I believe the losses at no load, and particularly the excitation losses, were unduly high. Now, if the excitation losses had been very small, the main current I^2R losses would have more than offset the decrease in watts taken by the hot field in a hotter room. It is quite clear that as the temperature runs up, the shunt coils take less watts, and also that the core losses become smaller. The windage increases somewhat, consequently the radiation of the heat is better, but I believe if the machines had been designed so as to be highly efficient at low loads, this free speed current would be extremely low, and I believe the result would have been opposite to what it was. I have certain machines in which the excitation only amounts to one-third of one per cent, and I believe if I make that same test on those machines the results will be different, because then the main current I^2R losses adjust the difference.

F. D. Newbury (by letter): The paper brings out a point of importance in the rating of electrical apparatus that is often overlooked, thereby leading in many cases to positions scarcely tenable. I refer to the fact that the only important temperature is the maximum temperature of parts adjacent to the insulation. There is such a large factor of safety required—representing the difference between the measured outside temperatures and the allowable inside temperatures—with our present methods of temperature measurement, that the results from such measurements are of little real value in judging a machine, and their approximate nature certainly does not justify a rigid adherence to the limits set.

Mr. Williamson's paper points the way toward a more rational basis for judgment, but the assumption made that all of the heat from the copper passes through the slot insulation into the laminations may be far from correct. There are at least three paths in parallel for the escape of heat from the copper.

1. Through the insulation to the laminations.
2. Through the insulation and wedge to the cooling air in the air gap.
3. Through the length of the copper to the exposed ends of the coils.

The division of the flow between these paths follows laws analogous to the more familiar laws in electric circuits. The drop in temperature along a given path is proportional to the heat "resistance" of that path, and to the heat "current" flowing; and in parallel paths the heat current divides inversely with the complete resistances. Or, a part of one path only need be considered, in which case the flow of heat will be determined by the resistance of the partial length considered and the difference in temperature (potential) involved. It is evident that if the temperature of the tooth laminations is equal to the temperature of the copper, no heat can flow from one to the other and there will be no drop through the slot insulation. In that case all

of the copper heat will flow through the copper to be liberated at the free ends of the coils and through the insulation adjacent to the wedge. This condition is approximated locally in many turbo-generators, it being relatively easy to secure low copper temperatures and difficult to secure uniformly low core temperatures. Or, to consider the opposite extreme, the tooth temperature may be so much lower than the copper temperature that all of the copper heat will flow through the insulation to the core. This is the assumption on which the author's formulas are based, and this condition is approximated in the short-circuit test mentioned by the author, the copper loss being increased 56 per cent above normal while the core loss is negligible. This explains why the test results and calculated results check. Similar short-circuit tests were made more than a year ago on a 14,000-kv-a. generator with the following results:

SHORT-CIRCUIT TEST, NORMAL CURRENT

Actual temperature of copper 52 deg.

Temperature outside of insulation against tooth laminations 34 deg.

Drop in temperature through insulation 18 deg.

Air temperature 26 deg.

The same generator was tested on open circuit and normal voltage with the following results:

Actual temperature of copper in different slots 42 deg. to 49.5 deg.

Temperature outside of insulation in contact with tooth laminations in one slot, 45.5 deg.

Drop through insulation, minus 3.5 deg. to plus 4 deg.

Air temperature 29 deg.

These results bring out very clearly the difference in heat flow with different distribution of losses.

In the tests referred to by Messrs. Chubb, Chute and Oetting (Fig. 2,) the effect of varying relative temperatures on temperature drop through the insulation may be seen.

In test *A* (open-circuit normal voltage), the teeth and core are of higher temperature than the copper, and the drop through the insulation between copper and tooth laminations is minus one deg., while the drop through the insulation between the copper and fiber wedge is plus 11 deg.

In test *C* (one-half normal current and full voltage), the corresponding "drops" are plus 3 deg. and plus 17 deg.

In test *E* (three-fourths normal current and nine-tenths normal voltage), in which the total temperatures are approximately the same as in *C* but in which the losses are differently distributed, the corresponding drops are plus 9 deg. and plus 14 deg. These figures show that instead of the drop between copper and iron sides of the insulation being proportional to the copper loss as in Mr. Williamson's formulas (2) and (3), the drop has increased faster than the loss (due to the increased flow of

heat caused by the lower core temperature): that this drop is much less than results from these formulas (due to the other paths available for the escape of heat), and that instead of the surface of the coil adjacent to the slot wedge being ineffective in dissipating heat, as assumed by Mr. Williamson, it is more effective than the surfaces adjacent to the laminations on which Mr. Williamson places the entire burden. The reason for this, of course, is the lower temperature of the air gap side of the fiber wedge compared with the temperature of the laminations.

The general method advocated by Mr. Williamson is much nearer the facts than methods of temperature determination now in use, but to be of practical value the formulas and method of calculation must be based on assumptions nearer the truth than the assumptions made by the author.

If the method and formulas developed in this paper are used to obtain actual copper temperatures from the measurements of temperature by resistance coils or thermocouples outside of the slot insulation, the results will be entirely misleading except on short-circuit tests.

B. A. Behrend: The question whether the total temperature is affected by the outside temperature is of great importance. I do not believe in the most plausible and lucid explanation rendered by Dr. Steinmetz and Dr. Kennelly, and the reason why it is not correct, if I may quote Prof. Adams, is that the radiation plays so small a part in the cooling of the modern electrical apparatus, that the beautiful, simple and plausible explanation is altogether too beautiful, too simple, and too plausible to be true!

Comfort A. Adams: I specified that that was true of a machine with normally good ventilation. It would hardly be true, perhaps, in a machine totally enclosed.

Concerning the hot spot temperature I understood Mr. Schuchardt to say that the exploring coils were placed under the wedges, between the wedges and the outside of the insulation. The drop of temperature through the insulation in this case is certainly such as to render the results of tests wide of the mark. The discussion by Mr. Newbury touches upon this same subject. I cannot quite agree with him. In a two-layer winding, where you have two bars separately insulated in the same slot, it is quite unlikely that much of the heat flowing from the lower bar will pass out to the surface by way of the coil above it and the wedge. The heat flow paths are in that case practically restricted to two, one through the solid insulation and the iron surrounding it and the other longitudinally to the coil ends. In a long core such as is found in large turbo-alternators, say 70 in. in length, it would take, in order to carry all of the heat longitudinally along the conductors to the coil ends, a difference of temperature of from 50 to 100 deg. cent. between the center of the conductor and the outer end, according to the current density in the copper. This difference in temperature increases with the

square of the length. It thus seems quite unlikely that any considerable amount of heat flows from the center to the ends. It seems still more unlikely that an appreciable amount of heat flows from the lower coil through the upper coil and the wedge. It must flow largely through the slot insulation. The results of Mr. Williamson's computations therefore seem to be quite reasonable.

R. F. Schuchardt: Just a word with reference to Dr. Adams's remarks with regard to the location of our exploring coils. It is true that these coils are laid between the wooden wedge and the outside insulation of the coil. It would be impracticable to put the coil directly adjacent to the high-tension armature copper. The problem is to get the exploring coil at the hottest point most practicably accessible and then allow for the probable higher temperature inside, and that is the reason we set 80 deg. for the measured allowable limit instead of 90 deg., even when measured so much nearer the hot spot than is possible with old-time methods.

B. F. Behrend: Suppose that the designer made a mistake and used a very heavy piece of copper; according to Mr. Burke's method of mind reading he would add 10 deg. for it, and he might equally well add 65 or 70 deg. The exploring coil may just as well be wound inside the coil. Coils should be so placed. It will help the designer and manufacturer, on the one hand, and the user, on the other hand; it would settle disputes if exploring coils could be wound inside the coil, and they should be.

Comfort A. Adams: It seems to me the explanation is the milk in the cocoanut, so far as the discussion we had this morning is concerned, and explains the recommendation of Mr. Torchio for a 75 deg. hot spot temperature, because his measurements were made apparently where the temperature was altogether likely 20 deg. or more lower than the actual hot spot temperature inside of the insulation.

Leo Schuler: I ask Mr. Schuchardt, when he made the measurements by means of that exploring coil which was outside the insulation, whether he measured the same coil by resistance, and what the relation of the two temperatures was?

R. F. Schuchardt: Our results showed about 30 deg. higher temperature with the exploring coil measured while the machine was loaded than by the resistance of the armature coil measured at the very earliest possible moment after the unit was shut down. Of course the armature temperature dropped immediately when the load was removed and while the unit was coming to rest.

Leo Schuler: Outside the insulation?

R. F. Schuchardt: Yes.

L. W. Chubb: In his discussion Mr. Durgin stated that his exploring coils were placed "some between coils, and some between coil and slot and some on the end turns." Mr. Schuchardt states that these same coils were placed "between the armature

coil and the wooden wedge," and adds that the problem is to place them in the hottest point accessible.

If the coils are located between coils as Mr. Durgin states, the difference of 30 deg. cent. between exploring coil and temperature by armature coil resistance is more probable. The temperature difference under the wedge and between the two coils can readily be seen by referring to the full load test shown under *D* in Fig. 2 on page 170. Thermocouple No. 17 shows the temperature under the wedge, and thermocouple No. 19 the temperature between coils. The thermocouple under the wedge is near the cool air gap; there is a great flow of heat from the coil and a large temperature drop through the insulation. Thermocouple No. 19 is placed where there is little heat flow through the insulation and the temperature outside of the insulation more nearly approximates the copper temperature.

W. F. Dawson: I should like seriously to propose that in those machines which have two-layer windings a thermocoil placed between the upper and lower layers will probably approximate the highest temperature in the machine. The outer coil has as a rule a greater loss than the inner coil, due to Foucault currents generated by stray flux threading the outer conductor, and this excess loss probably about compensates for slightly better ventilation which the outer coil receives from proximity to the air gap. The temperatures of the upper coil and the bottom coil are approximately the same, and, therefore, there will be practically no exchange of heat between them. This middle point, therefore, should approximate the maximum temperature of the copper.

Charles P. Steinmetz: The only way of locating and measuring the hot spots would be by distributing exploring coils all along the inside winding of the high-potential coil, but today, when all station operators insist on spreading high-tension supply over a long distance and controlling it by low voltage, I do not think there would be any enthusiasm, on the part of stations which operate at 11,000 and 13,000 volts, to employ Wheatstone bridges or other such apparatus to measure the coil.

As regards the relative conductivity of the alternative paths, we are at cross purposes because we speak of different types of machinery. On the one hand, one engineer has in view high-voltage turbo-generators with 0.3 in. thickness of insulation, and a coil with several sq. in. of copper section, where the heat production is very large, while on the other hand, in the moderate or low-voltage machines, with small coils, the conduction along the copper may be negligible compared with the heat conduction across the coil insulation, so that you see there are different classes of machines, and what applies to one does not necessarily apply to the other.

Alexander Gray: It seems to me that if we put resistance coils next to the copper of the machine, they must be put near the neutral, and the neutral grounded.

There is another point of some interest. In a machine with a two-layer winding, the winding being well laminated so that there are no eddy currents in the conductors, the temperature of the two layers is the same, there is no flow of heat between the upper and the lower layer, and therefore a thermocouple placed between these layers must give very nearly the copper temperature, because there is no temperature gradient if there is no flow of heat.

I want to record the case of a large machine in Montreal which has a temperature rise of 40 deg. cent., measured by thermometer on the ends, and a temperature rise of 127 deg. cent. measured by the resistance coils placed between the upper and lower layers of the windings. It is a machine with deep conductors insulated with mica. The eddy current loss in the deep conductors is very large, and there is a flow of heat from the coil in the top of the slot to that in the bottom.

B. A. Behrend: If Dr. Steinmetz means that it is necessary to distribute 11,000-volt exploring circuits all over the power house in order to get the inside temperature of a high-tension generator, I venture to say that his statement is rather audacious, because you might easily put a small exploring coil in one of your high-tension coils, and bring the leads back to an instrument, which you might attach to the turbo-generator in a manner similar to the method of attaching steam gages to high-pressure steam turbines, without carrying high-tension current all over the power house, as he suggested.

R. B. Williamson: The temperature gradient has much to do with hot spots in a long generator. The gradient through the insulation of high-voltage machines is higher than many realize, and in machines having very long cores, we cannot count on much heat passing from the center of the machine out to the end.

As Prof. Adams has pointed out, the difference in temperature necessary to set up a flow of heat from the center to the end, increases as the square of the length. Considering the center of a long machine, nearly all of the heat liberated in the copper must pass through the insulation to the iron. On this assumption it is possible to calculate the temperature difference between copper and iron closely enough to give us some idea of the probable internal temperatures. In the case of high-voltage machines where the thickness of insulation is considerable there will be a relatively high temperature gradient, and it becomes a question to decide whether it is better to use lower voltage with thinner insulation and use step-up transformers, or use the high voltage with accompanying higher internal temperature.

B. G. Lamme: I want to refer to one point, namely, the measurement of temperature of high-voltage armature coils by means of thermocouples placed inside the insulation. I think that is all right as a research method, or one for determining temperature gradients in general. If we find by test that thermo-

couples placed between upper and lower coils in the same slot in a high-voltage machine, give practically the same temperature as thermocouples located inside the insulation, then we have gotten the information we need for practical purposes. I think therefore that the use of thermocouples inside the insulation would be for the purpose of calibration only, and will not become a commercial method of measurement, as there are very serious objections to such an arrangement.

Prof. Adams has spoken about the very small amount of heat conducted from the middle of a turbo-generator winding to the outer end. This is true in some cases, but in all cases there is a certain amount of heat conducted out which serves to reduce the internal drop through the insulation at the hottest point. Considering that a large turbo-generator may be 50 deg. hotter in the center of the winding than in the end winding, my calculations show that, except in very extreme cases, the longitudinal heat conduction is an item which should be considered in the calculations.

James Burke: I have prepared some notes on the papers now under discussion, in which I have, I think, shown that all the results are consistent, that the corrections for difference in temperature of the surrounding medium can be made and can be made intelligently. In general, the results shown in the tests of motors, and exploring coils, and certain experimental coils, all agree with each other within a very close margin. The negative and positive results are to be expected, and I think from the data contained in these various papers that we will be able to determine exactly what temperature correction should be introduced in the Rules. I think that a temperature correction is necessary, in view of the fact that one of these papers states specifically that certain motors fulfilled a temperature guarantee in summer, and failed to fulfill the guarantee in winter, and on retest in summer fulfilled the guarantee again. So that the importance of temperature correction seems to be supported by the facts in the papers now before us.

James Burke: (by letter) In the paper by C. P. Steinmetz and B. G. Lamme, reference is made to temperature correction as follows:

"The variation of the temperature rise has heretofore been considered as having a definite relation to the temperature of the cooling medium. However, it appears that it does not follow any definite simple law, but it is sometimes positive and sometimes negative, so that no satisfactory correction for room temperature is possible at present."

Also the following recommendation is made: "No temperature correction should be made for variation of the cooling temperatures from the reference temperature of 25 deg. cent."

From the number of very interesting papers presenting data on this subject, it would appear that a satisfactory treatment of this temperature correction can be arrived at, and it seems that

the apparent confusion from the correction being sometimes positive and sometimes negative, should be fully explained.

In the existing rules, temperature correction is covered by rule No. 269, where it is stated that the correction is "On account of difference in resistance."

The adopted standard room temperature is 25 deg. cent., and the temperature coefficient for the resistance of copper at this temperature is given in appendix *E* of the present Rules, as 0.00386 for copper of 100 per cent conductivity, and this figure seems to be generally used. Taking this figure as a basis for correction, it would appear that the correction should be 0.386 per cent per deg. instead of 0.5 per cent as in the present rules.

If we consider a condition of room temperature of 40 deg. cent., which is 15 deg. above the adopted standard room temperature, all the copper resistances will be 5.8 per cent higher than at the standard room temperature of 25 deg. cent. For all copper carrying a constant current, as, for example, the shunt field of a generator in which the exciting current is kept constant for the purpose of maintaining constant voltage, the watts lost will be increased by 5.8 per cent. In the shunt field of a motor operated from a constant-voltage supply circuit, the result of the higher resistance due to higher room temperature is to reduce the current flowing in the circuit, and the watts lost in the circuit are reduced 5.8 per cent; thus we have an increase in the watts lost in a generator field and a decrease in the watts lost in a motor field, when the room temperature is higher than the adopted standard of 25 deg.; and for room temperatures of 40 deg. cent., the difference between a generator field and a motor field is 11.6 per cent. If a generator and motor were directly comparable, under this assumed room temperature of 40 deg., if the temperature increase on the motor field is 50 deg., the increase on the generator field would be approximately 6 deg. higher, or 56 deg. cent. If the value of the cooling medium is constant, we will then have a positive correction in the generator and a negative correction in the motor. If, however, the watts lost are kept constant rather than the current or the voltage, there would be no temperature correction if the value of the cooling medium remained unchanged, because in maintaining constant watts the increase in the resistance of the copper would be compensated for by a decrease in the current flowing.

Sometimes the fact is misunderstood, that the reason for temperature correction is due to change in watts lost on account of change in resistance, occasioned by the difference in temperature. For example, in the paper by Blanchard and Anderson, page 296, in referring to their curves of Fig. 3, which are based on keeping the watts constant, they say: "The variation according to these curves is about 0.15 deg. per deg. cent. variation of air temperature, in the opposite direction to that assumed in the present Standardization Rules."

As pointed out above, there would be no temperature correc-

tion for constant watts, but there would be a positive correction for constant amperes, and a negative correction for constant voltage applied to a coil.

The next important consideration, is variation in the quality of the cooling medium. In the present Rules the assumption seems to be that the cooling medium is constant, or, in other words, that with some definite watts per sq. cm. the temperature increases above the surrounding air would be the same with air at 40 deg. as with air at 25 deg. In the paper by J. J. Frank and W. O. Dwyer, entitled *Temperature Rise of Stationary Induction Apparatus*, it is shown that the radiation of heat is better with higher surrounding temperature, and taking a standard temperature of 25 deg. cent., the radiation value improves by 0.73 per cent for each degree increase in surrounding temperature. In the same paper it is shown that the convection becomes poorer with higher surrounding temperature. It will, therefore, be evident that the change in value of the cooling medium will depend upon how much of the heat is taken care of by radiation, and how much by convection. This influence is shown in Fig. 8 of their paper, in relation to tank dissipation, from which it will be seen that with a 50 deg. cent. increase in temperature, the correction for the cooling medium is as follows:

No convection	plus 0.73 per cent.
Combined radiation and convection from plain cast-iron surface	" 0.51 per cent.
Combined radiation and convection from simple corrugated surface	" 0.36 per cent.
Combined radiation and convection from compound corrugated surface	" 0.21 per cent.

The foregoing figures are based on stationary surfaces, without any air circulation caused by the moving part in the machine, or caused by fan for forcing air through the machine. With air circulation, the proportion of heat dissipated by convection increases rapidly, and it is not unusual to have the effect of convection ten times as great as the effect of radiation. On the compound corrugated surface, if by air circulation the convection is made four times as great as the radiation, the improvement in radiation due to higher temperature is just counterbalanced by the depreciation in convection, so that the value of the cooling medium becomes constant. In the same way it will be seen that with the simple corrugated surface, when the convection is about seven times the value of the radiation, the correction becomes zero and the value of the cooling medium constant. Similarly, with plain cast iron surface, when the air circulation is sufficient to make the convection approximately

ten times the radiation, the correction becomes zero, and the value of the cooling medium constant.

This paper by Frank and Dwyer, which contains some valuable tests, recommends for air-blast transformers a correction of one-half of one per cent per deg. variation for 25 deg. cent., which incidentally is the same correction as in the present A. I. E. E. Rules. This is only recommended for air blast transformers and not for other types of transformers.

In the paper by Blanchard and Anderson, the test shown in Fig. 3, curve 3, for air pressure of 760 mm., figures out a negative correction of approximately 0.3 per cent per deg. This is for a coil suspended in still air and is probably comparable with a simple corrugated surface. The deduction which I have made from the paper of Frank and Dwyer, shows for a simple corrugated surface a negative correction of 0.36 per cent per deg., so that it is a substantial agreement.

In the paper by C. E. Skinner, L. W. Chubb and Phillips Thomas, entitled "Effect of Air Temperature, Barometric Pressure and Humidity on the Temperature Rise of Electrical Apparatus," tests are given on a coil maintained at constant watts of approximately 32, and with air circulation for the purpose of cooling the coil. These tests are tabulated in table No. 1, and show that the increase in temperature of the coil was practically constant throughout a range of temperature of the cooling air, of from 30 deg. to 64 deg. If the coil is considered as a simple corrugated surface, then their test agrees with the deductions which I have made from the paper of Frank and Dwyer, with a convection value of seven times that of radiation. From the description of the arrangement for this test and the blower for putting the air through the testing box, this amount of convection in relation to radiation would be easily expected, and therefore there is substantial agreement.

From the tests of Skinner, Chubb and Thomas, above referred to, where they show practically zero correction for a large variation in air temperature, and with constant watts, it is evident that if this coil were carrying a constant current it would have a positive correction of 0.386 per cent per deg. cent., and if it were working under a condition of constant voltage applied, it would have a negative correction of the same amount.

The paper by Maxwell W. Day and R. A. Beekman, entitled "Effect of Room Temperature on Temperature Rise of Motors and Generators," shows some interesting tests from which deductions can be made.

The results given in this paper are based on tests which appear to be at constant speed; for example, Figs. 4, 5, 6, 7, 8, and 9, are all marked "825 rev. per min." However, the description of the test shows that they were operated at constant voltage. The average difference in final temperature of fields between the low temperature test and the high temperature test in each figure is about 21 deg., which would make about 8 per cent differ-

ence in field strength, due to the higher resistance and consequently less current in the fields. This would result in a speed difference of approximately 4 per cent. As most of these tests were with fans for circulating air through the motor, and apparently the fans directly connected to the motor, this difference in speed would make a great difference in the amount of air circulated, as the amount of air circulated by a fan increases very rapidly with increasing speed of the fan. It would appear therefore, that at least part of the negative temperature correction in all these figures could be accounted for by a higher speed of motor due to the weaker field with higher temperature, and consequently increased air circulation.

Taking the figures from Figs. 4 to 12 in the said paper, and considering the bearing temperatures, the average of all the bearing temperatures is a correction of minus 0.75 per cent. If these bearings are considered as plain cast-iron surfaces, we would have a comparable figure from the deduction made from the paper of Frank and Dwyer of minus 0.51 per cent. The probable difference in speed of 4 per cent would make a difference in torque at the same load of about 4 per cent, which would mean less pressure on the bearings and consequently negative correction. If this is taken at 0.2 per cent per deg., which is figured from the average temperature, and deducted from the 0.75 per cent average from the test, the difference is 0.55 per cent, and is comparable with the 0.51 per cent for plain cast-iron surface referred to, thereby approaching substantial agreement.

Similarly, the average of all frame temperatures gives a correction of 0.46 deg. per deg. and agrees very closely with the 0.51 per cent per deg. for plain cast-iron surfaces.

Considering now the correction for shunt field by resistance, averaging all the tests shown in Table I, we get a negative correction of 0.31 per cent per deg., and similarly the average for shunt field by thermometer is 0.389 per cent per deg. These figures are directly comparable with the present A. I. E. E. rules of 0.5 per cent per deg., which, as pointed out, if based on the temperature coefficient of copper, should be 0.386 per cent per deg. The average of the two methods of tests, namely, by resistance and by thermometer, is 0.354 per cent per deg., which is very close agreement with the temperature coefficient of copper, namely, 0.386 per cent, and can be considered in substantial agreement.

In the paper by Day and Beekman, an attempt is made to draw some average from commercial tests, for example, Fig. 13, which shows the armature conductors' temperature increase on 98 machines, which are supposed to be alike. In these tests there are thirteen machines tested at 20 deg. cent. room temperature, and the tests appeared to show temperature increases varying from 23 deg. to 38 deg., or a variation of 65 per cent in the increase in temperature. Similarly, in Fig. 15, out of 11 machines tested, at a room temperature of 20 deg. cent.,

the shunt field temperature increase varies from 22 deg. to 45 deg., or over 100 per cent variation. It would therefore seem that any conclusion of averages drawn from these commercial tests should be avoided.

From all the foregoing and from the information contained in the various papers, it would seem that the present rules can be corrected so as to give a fairly accurate basis for temperature correction. The argument against continuing a temperature correction in the rules, seems to be that it is too close a refinement when the large variations in actual temperature measurement are taken into consideration. Nevertheless, the great importance of accurate determination of temperatures will doubtless bring about more care in this direction and better agreement between tests in the future, and probably also better methods of taking temperatures. As pointed out, the difference between a dynamo field temperature and a motor field temperature may be as much as six deg. at a surrounding room temperature of 40 deg., and yet have no difference at 25 deg. surrounding temperature, and it would seem that such a large difference should not be overlooked.

The importance of establishing proper rules for temperature correction is brought out very strongly in the paper by Day and Beekman, from which I quote:

"In one particular case some motors were tested in the summer and easily met the specified heating limits, but when the customer installed them in the following winter, and tested them, some of the heating limits were exceeded, while on retesting them again in the following summer the machines again easily met the specifications."

Now in this particular case, on account of not applying proper temperature corrections, the heating limits were exceeded. In other words, it appears that the machines did not fulfill the specifications. This might have been a cause for rejection of the machines, and yet the trouble was not with the machines, but was in not having a proper rule for correction.

If the motors in question were totally enclosed machines without forced draft ventilation and operated in a summer temperature of 35 deg., with an increase in temperature of 50 deg., then operated in a winter temperature of zero, the temperature increase might become 66 deg. for the shunt field, on account of increase in watts, due to more current flowing in the shunt fields, and also on account of decrease in quality of the cooling medium. In the assumed case, the correction for cooling medium was taken at the same as for plain cast-iron surface, namely, 0.51 per cent. which would probably be correct on account of being an enclosed motor and not having air circulation to increase the effect of convection.

In this assumed case with 35 deg. air temperature and 50 deg. increase, the ultimate temperature would be 85 deg., whereas with zero air temperature and an increase of 66 deg., the ultimate

temperature would be only 66 deg. Therefore the motor would be perfectly safe, but would not be filling a temperature specification of 50 deg. increase, unless some temperature correction were applied.

If the motor in question was not a fully enclosed motor, or if it had forced circulation, the lower temperature would result in stronger fields and probably about 14 per cent difference in the amount of air circulated through the motor. So that the temperature increase would be greater, not only on account of increased watts in the field, but also on account of much less air being passed through the machine for cooling it. This condition might readily result in the shunt field having an excessive increase of temperature, compared with specifications, unless some temperature correction were applied.

Charles P. Steinmetz: I wish to say that when the Committee recommended not to make any temperature corrections, it was under consideration that the previously used temperature correction was incorrect, and that the evidence thus far available shows that there is a change of the temperature rise with the room temperature, but that no law has yet been derived from these tests. Since we have not yet been able to formulate a law, all we can do is to say that in testing we shall, as closely as possible, try to get the room temperature near the standard temperature.

A. E. Kennelly: I think it is a very interesting fact that the Standardization Rules are encountered by a question of pure science as to what is the law of the dissipation of heat energy from a heat body of a given form, and it is a remarkable fact, also, that whereas steam engineers are constantly investigating the laws of heat, for determining the input capacity of their machines, in order to utilize the heat, we are faced with the opposite difficulty of finding how far we can dissipate heat, and get rid of it. It is curious that heat should be the common science in which we both find limitations.

In regard to Dr. Langmuir's paper, he proposes a very interesting method for determining the dissipation by convection from a hot body. He proposes to consider, for example, that a round stationary wire which is heated by an electric current carries a layer or sleeve of stationary air around it, that the heat is conducted through that stationary layer, and then dissipated in any manner you please beyond that stationary sleeve. This hypothesis is likely to conflict with fact. We think there is evidence to show that the air is not stationary in the immediate neighborhood close up to the hot wire. Dr. Langmuir's formula if it will give us correct answers may be of great value to us, but it does not follow that the physical facts are in accordance with this hypothesis, even if the formula based on this hypothesis gives correct results.

In regard to dissipation of energy by free convection, in our paper presented before the Institute three years ago we first showed that when a thin wire was subjected to forced convection

in air, quadrupling the speed of convection doubled the convected power, and that has been since corroborated by Prof. Norris in England. It was later discovered in the archives of a French society that Boussinesq had originated a formula leading to this result. Dr. Russell has recently developed Boussinesq's formula in practical form, and has shown that the heat should dissipate as the square root of the pressure as well as the square root of the velocity. We have lately checked this by experiments not yet published.

L. W. Chubb: In our paper on temperature rise, the curve of Fig. 2 shows a constant rise at all temperatures. This result seems to be somewhat contradictory to some of the other papers. In these tests the temperature of the walls was kept the same as that of the cooling air, and if there is any difference in convection due to the change in the viscosity of the air, this difference must be small, with forced convection, and be offset by the fourth power law of radiation through equal range of temperature at higher temperatures, within the range of temperature shown.

In the tests the ratio of dissipation by convection to radiation was very high, and if there is any great difference in convection at different temperatures, it would certainly more than offset the change in radiation.

The same apparatus illustrated was changed so that the cubical box consisted of glass plates. In this case the radiation to outside objects at ordinary temperatures caused a much lower temperature rise above the circulating air, when the air was at high temperature. This shows that corrections of temperature rise should not be based on air variations from 25 deg. cent. alone, and that the temperature of surrounding walls and objects will have a greater influence than the air variations.

If corrections are to be based on variations of air temperature alone the manufacturer can profitably entertain his customer's witness in a palm garden and do his testing in a glass conservatory where the air temperature will generally be high and most of the radiation will be to space at absolute zero.

Selby Haar: Dr. Langmuir gives a number of data on thermal conductivities and resistivities of various materials, but I believe he has overlooked a series of researches by a German physicist, Dr. Nusselt, whose method seems to be quite worthy of study. He used two concentric spheres between which he put the heat insulator which was under investigation, and he also was able to study the differences in the heat resistivities at various temperatures.

Leo Schuler: In regard to the influence of air temperature on the rise of temperature, Mr. Burke says that he has worked out a method of taking this into consideration. According to theory, and also according to the experiments shown in the paper, the influence of air temperature will be the more pronounced the more heat is taken away by radiation, though the difference will probably be greater in an enclosed motor, as is also shown in

the paper, while, for instance, in the large turbo-generator where all the heat is taken away by convection, by air, there will be practically no difference. Could not Mr. Burke give us some idea how he proposes to take this into consideration for the correction to be made in the rules?

James Burke: That is covered in my written discussion.

E. W. Stevenson: Dr. Kennelly was the author of a very useful and interesting table, published twenty-five years ago, upon the carrying capacities of cables, in which he laid particular emphasis upon the fact that a dull black color on the outer surface made the carrying capacity of the conductor very much more than what it was if it were polished or bright.

I would like to ask Mr. Dushman whether, in making his experiments, he tried the value of the different colored pigments on the outside of cables carrying overload currents, and if in doing so there were any differences in the carrying capacity of these cables. Of course, it is understood that these cables are all hanging in the open air. It is possible there would be no difference with cables lying in ducts, whatever their color is.

R. W. Atkinson: I wish to confirm what has been said by Mr. Dushman about specific heats. We have looked up data for a good many materials and have tested a number of others, and find these figures are closely the same for the different materials and about of the value given.

I wish to mention that we have obtained considerable additional data since preparing this paper, which will be published in the TRANSACTIONS in a form which will make our data of much more practical use. I wish further to state what has been the basis of the formulas and equations which we have given here. These are all a result of actual tests; careful measurements have been made with thermometers and thermocouples of the temperature rise of many different sizes and types of cables. For convenience, greater accuracy, and brevity we put these in the form given in our paper.

R. W. Atkinson (by letter): In order that the constants "a" and "b" on pages 327 and 328 may be compared with other constants which are presented at this time, we may state that they correspond to a thermal restivity of approximately 1000 cent. degrees per watt per centimeter cube, and to 1200 degrees per watt per square centimeter, respectively. The neglecting of temperature coefficient in the formulas means that we assume that the negative temperature coefficient of heat resistance approximately balances the coefficient of copper ohmic resistance.

Since preparing our paper, we have made a number of further tests, and have correlated our results so that they may be conveniently applied to determining the temperature of cables installed in underground conduit systems. We are giving these data for predetermining both the ultimate temperature rise and for determining the temperature with loads of comparatively

short duration. Reference will be found in what follows to some of the other papers presented at this Midwinter Convention, and also to a paper by C. T. Mosman published in the 1912 TRANSACTIONS, Vol. XXXI, Part I, page 755.

The formulas and equations which we have given, and the tables which we give herewith, with one exception which will be mentioned, are a result of direct test, careful measurements having been made with thermometers and thermocouples, also a few by rise of resistance method, of the temperature rise of many different sizes and types of cables. For convenience and brevity, and to increase the range of application, we have put these in the form given.

Table III, herewith, shows the current necessary to produce a rise in temperature above surroundings, of 25 deg. cent., for cables insulated with 1/8-in. (3.17-mm.) saturated paper and covered with a bright new lead sheath. The constants used are those just mentioned. The rise of temperature of a cable above a duct wall surrounding it is the same as the rise of the same cable in free air. This is indicated in the theory given in Langmuir's paper and is also borne out by tests made by us. As stated, the value assigned to a is correct for a new bright sheath, either in air or in conduit. This value indicates that the radiation from the sheath is about one-third of that from a perfect "black body." Painting the sheath black will reduce the temperature rise of the sheath from 20 per cent to 25 per cent below the value used in the table. It is indicated by Langmuir's theory that, depending upon the relation in size of the cable and the enclosing duct, the rise of the sheath might be increased slightly or considerably reduced below the value given, but we do not believe either condition likely to become important. The value given for b is a safe value for ordinary paper or varnished cloth cables. Our tests show, in most cases, a rise of copper above lead of 10 per cent or 15 per cent less than this, but it is believed that this value is as low as it is safe to use. The value given for varnished cloth by Dushman is 25 per cent lower than this. The same author gives a value for rubber which is 63 per cent of the value given here for paper. Table III should be used as given, for ordinary cases, and for those cases where it is not necessary to use absolutely the maximum allowable capacity. The values given will always be safe for the thickness of insulation given. Table IV gives correction factors for various thicknesses of insulation and shows how the total differences of temperature between copper and the surroundings of the cable are distributed, and thus makes it possible to make use of the correction factors given above where it is desirable and necessary. It will be noted that the total temperature rise is very nearly constant with the various thicknesses of insulation given.

Tables V and VI correspond to tables numbered III and IV respectively, tables numbered V and VI being for three-conductor cables.

Having now the temperature rise of the copper of cable above the duct walls, we will give data for determination of the rise of the duct walls above the surface of the earth. On account of the many variations which may occur with different types of duct system and laid in different kinds of earth which is itself at

TABLE III.—SINGLE-CONDUCTOR CABLE

CURRENT REQUIRED TO PRODUCE 25 DEG. CENT. RISE ABOVE SURROUNDINGS, AND WATTS LOST PER FOOT

Size B. & S. G.	Cir. mils	Current in amperes	Watts lost per foot at 66 deg. cent.
14		22	1.45
13		26	1.58
12		29	1.59
11		34	1.58
10		38	1.66
9		44	1.86
8		51	1.97
7		58	2.00
6		67	2.03
5		77	2.14
4		89	2.21
3		103	2.31
2		119	2.51
1		138	2.58
0		159	2.90
00		185	3.12
000		215	3.37
0000		250	3.62
	250,000	279	3.75
	300,000	314	3.98
	400,000	381	4.40
	500,000	442	4.74
	600,000	501	5.07
	700,000	555	5.30
	800,000	610	5.61
	900,000	661	5.90
	1,000,000	712	6.15
	1,100,000	759	6.32
	1,200,000	807	6.55
	1,300,000	851	6.73
	1,400,000	895	6.95
	1,500,000	941	7.17
	1,600,000	984	7.34
	1,700,000	1024	7.50
	1,800,000	1063	7.58
	1,900,000	1112	7.89
	2,000,000	1149	7.94
	3,000,000	1500	9.10
	5,000,000	2100	11.6

various and somewhat unknown temperatures, we believe that a direct measurement of duct temperature in combination with the data given above is the practical method of determining temperatures of existing installations. For purposes of previous calculations of new installations, we present herewith results of

tests in a form for future use. Tests recently made by us show a difference of temperature between the inner and outer walls of a terra cotta duct 0.8 in. (2 cm.) in thickness to be 0.35 deg. cent. per watt of actual loss per foot length of conduit. These tests were made upon 3¼-in. (8.25-cm.) conduits, the difference in the temperature given being that through a single wall. We may thus consider that the temperature of the outside wall of the duct is lower than the temperature of the inner wall by 0.7 deg. cent. per watt per foot. This is on the assumption that the heat from the cable is radiating freely from each of the four walls. In order to measure the temperature of the duct walls surrounding any cable, it is necessary only to measure the temperature in an adjacent idle duct at the same distance from the outside of the conduit or the temperature of a duct adjacent but nearer the center of the conduit system. In the former case, the

TABLE IV. SINGLE-CONDUCTOR CABLE

A—Rise in temperature attained with current in Table III.
B—Rise of sheath in per cent of total rise.

Size B. & S. G.	Cir. mils.	4/32 Paper		8/32 Paper		16/32 Paper	
		A Deg. cent	*B* Per cent	*A* Deg. cent.	*B* Per cent	*A* Deg. cent.	*B* Per cent
14		25	52	25.6	36		
11		25	56	25.7	38	27.4	23
8		25	59	25.8	41		
2		25	66	26.4	47		
0		25	68	26.5	50	30.1	32
0000		25	70	26.9	52		
	500,000	25	73	27.5	56		
	1,000,000	25	75	28.2	58	33.6	38
	2,000,000	25	76	29	60		

temperature of the idle duct will be lower by not more than a very few degrees, which can be estimated from the data just given, and in the latter case the temperature of the idle duct will be very nearly the same as the walls of the working duct. A still more satisfactory way of measuring the temperature of the duct wall is to make the measurement actually within the working duct, but *after cutting off the current from the cable within*, for from one-half hour to two hours. This is allowable on account of the great amount of time required by the duct system to change in temperature as compared to the time required for the cable to change. If measurement of cable within a working duct is taken when there is a great difference between the temperature of the sheath and the temperature of the duct walls, it is obvious that it is not known which temperature is being measured. With any number of cables distributed throughout any duct

system, the rise of the system above the surface of the earth is quite closely proportional to the total energy dissipated in all of the cables. With any given type and size of conduit construction, we may say that the temperature rise of the system is equal to a certain number of degrees per watt lost per foot of duct structure. The tests previously referred to, made by one of the authors at Niagara Falls, indicate that the rise in temperature of the outer duct of a 12-duct system is equal to 0.67 deg. cent. per watt loss per foot of structure. The rise in temperature of a duct not adjacent to the earth may be taken as 0.8 deg. per watt loss. Mosman's tests (A. I. E. E. TRANS. Vol. XXXI, p. 771) give data for calculating the temperature rise of a conduit system containing 81 ducts. This is a fibre conduit laid in concrete. The center duct contained no cable and the rise of this and the nine surrounding it can be taken as 0.35 times the total watts lost in the system. The temperature rise of the surrounding rows taken in order may be taken respectively as 0.29, 0.21, and 0.13 deg. cent. per watt lost per foot of structure. Sufficient data are not available to make a good generalization.

TABLE V.—THREE-CONDUCTOR CABLE INSULATED WITH 3/32 PLUS 3/32 PAPER

CURRENT REQUIRED TO PRODUCE 25 DEG. CENT. RISE ABOVE SURROUNDINGS

Size	Cir. mils	Current in amperes	Watts lost per foot at 66 deg. cent.
14		17	2.6
13		19.5	2.7
12		22	2.7
11		25	2.8
10		29	2.9
9		33	3.1
8		38	3.3
7		43	3.3
6		50	3.4
5		57	3.5
4		66	3.7
3		76	3.8
2		88	4.1
1		101	4.3
0		117	4.7
00		136	5.0
000		158	5.5
0000		183	5.8
	250,000	204	6.1
	300,000	231	6.5
	400,000	278	7.0
	500,000	322	7.5
	600,000	363	8.0
	700,000	402	8.3
	800,000	438	8.6

Very often, a formula similar to that given by the authors has been given for the temperature rise of cables carrying currents for short periods. With the formula as a starting point and based on the assumption that the insulation takes the heat with the same rapidity as the copper conductor, theoretical curves have been deduced showing the temperature rise after various lengths of time. Probably the error due to this wrong assumption is seldom very large. The data given in the paper of the authors are based on tests of a number of different sizes, varying from No. 6 to 1,000,000 cir. mils. These experimental

TABLE VI. THREE-CONDUCTOR CABLE

A—Rise in temperature attained with current in Table V.
B—Rise of sheath in per cent of total rise.

Size B. & S. G.	Cir. mils	$\frac{3+3}{32}$ Paper		$\frac{8+8}{32}$ Paper	
		A Deg. cent.	*B* Per cent	*A* Deg. cent.	*B* Per cent
11		25	58	21.2	35
5		25	59	23	37
0		25	61	25.7	37
	500,000	25	62	29	39

results were then put in a form closely resembling the simple theoretical formula, thus largely combining the advantages of pure theory and pure experiment. We believe that our data can be expressed in a form somewhat more convenient for some uses, as given in Table VII. We have made one or two small corrections. This table shows the length of time required for different sizes of cable to reach different percentages of final temperature change, after an alteration in current strength. The data are so given that the temperature rise due to excessive overloads for short periods can be computed. If a steady current has been flowing, and an additional current is suddenly applied, the table is applicable to the temperature change due to the change in current. We do not advise application of these data to conditions which will actually cause a rise greater than that normally allowed; however, in the calculation of the final temperature rise to be used in connection with the table, one should neglect the temperature coefficient, simply assuming the final temperature rise for any current to be proportional to the square of the current.

The data so far given for short time temperature rise of cables apply to the rise of temperature above the surroundings. The heat capacity of the duct structure for underground cables, is very great as compared with the heat capacity of a cable itself,

and consequently the temperature rise of the duct structure is very slow. There are not enough experimental data to make general applications. Table VIII is computed on the assumption that the only portion of the duct structure to store heat from the cables is that portion of the duct structure immediately surrounding the cable. This is far on the safe side, as shown by theory and by the results of some tests which have been compared with these tables. If it is desired to apply these tables to learn how long an experiment on an underground structure must be carried on to reach a steady temperature, it would be well to double the length of time given in the table. The columns in the center of the table (2*a* and 2*b*) may be taken as representative of most duct structures where the rise of the structure itself is important.

In order to make tables of carrying capacity of general use it is necessary to base the tables upon conditions which cause

TABLE VII

B. & S. G. or cir. mils	Time in minutes with 5/32 insulation							Bare
Per cent of final rise	10%	20%	30%	50%	70%	80%	90%	10%
6	0.52	1.2	2.4	5.3	11	16	30	0.38
4	0.66	1.6	2.8	6.6	14	21	35	0.47
2	0.90	2.1	3.8	8.5	19	30	40	0.63
0	1.2	3.0	5.5	12.5	25	37	55	0.9
000	1.8	4.5	8	18	37	50	72	1.2
300,000	2.9	7.2	12	25	48	65	92	2.0
500,000	4.0	9.8	16	31	57	78	115	2.8
1,000,000	6.8	15	24	49	85	120	165	4.7
2,000,000	9.5	21	34	67	115	155	230	7.0

Time required to reach various percentages of final temperature change. Time for bare conductor to reach 50 per cent and 90 per cent of change is 6.6 and 22 times as long, respectively, as to reach 10 per cent of final temperature change.

only the true ohmic loss in the conductors. This makes the tables true for all ordinary conditions. However, conditions do arise which greatly increase the losses, and these must sometimes be taken into account. The effect of dielectric loss has already been mentioned. Other losses which occur are analogous to certain losses which occur in various electrical machinery. Skin effect has been thoroughly treated in many places. When a single-conductor cable carries alternating current, if there be a lead sheath, there may be a very considerable loss induced in that sheath. This is treated and curves showing its amount are given in a discussion by the writer in the A. I. E. E. TRANS., Vol. XXXI, page 806. There is another loss which may sometimes occur but which, under almost all ordinary circumstances, is insignificant. Alternating current flowing in any conductor produces a field in adjacent conductors and a resultant eddy current loss. If there is already a current flowing in the other

conductor, this merely constitutes a distortion of the distribution of the current, but the effect upon the loss is the same. To show the magnitude of this, we may state that if a cable of 2,000,000 cir. mil cross-section, enclosed in a sheath of lead having a diameter of 3 in. (7.6 cm.) and a thickness of 1/8 in. (3.1 mm.), is placed immediately adjacent to a cable of similar construction, a loss will be induced in the lead sheath of one by 60-cycle current in the other, of about 10 per cent of the ohmic loss in the one carrying current. It is possible for the loss in the copper conductor, induced in the same way, considerably to exceed this, unless the resistance between strands is unusually

TABLE VIII

PER CENT OF FINAL TEMPERATURE ATTAINED WITH LOADS OF DIFFERENT PERIODS

Column "a" for first application of load.
Column "b" for loads repeated daily.

Time in hours	1-*a*	1-*b*	2-*a*	2-*b*	3-*a*	3-*b*
1/2	12	12	6	6	3	3
1	22	22	12	12	6	6
2	40	40	22	23	12	12
3	55	55	31	32	17	18
4	64	64	40	41	22	25
5	72	72	47	48	27	31
6	79	79	55	56	31	36
7.5	85	85	62	64	38	46
10	92	92	72	75	47	63
15	97	97	85	87	62	75
20			92	97	72	87
24			95	100	79	100
30					85	100
48					95	100

Columns 1 are for system where one watt loss per foot in each cable causes 16 deg. cent. rise of duct structure.

Columns 2 are for system where one watt causes 8 deg. rise.

Columns 3 are for system where one watt causes 4 deg. rise. The time constant will not be shorter than this for any system.

high. This loss is proportionately less when the absolute dimensions are smaller, and also varies as the square of the distance between centers and inversely as the square of the frequency. It will be seen that this is ordinarily insignificant. It must be borne in mind that, wherever any of these losses occur, allowance must be made in computing the temperature rise and the resultant carrying capacity. This last-mentioned and usually insignificant loss must not be confused with the loss which occurs when the sheaths are connected together. This may exceed the conductor I^2R.

H. M. Hobart: Am I right in stating that Dr. Langmuir can tell fairly correctly what would be the temperature correc-

tion for any electric machine? Could he not, in a fairly reasonable space of time, figure out what the temperature correction should be?

S. Dushman: I believe he could, especially by taking into account the total losses as being due to the convection through the film and the radiation; taking that into account he can figure out the loss in each case, and I believe Dr. Langmuir will probably differ with what was said about the evidence being contrary to the existence of the film, because he has found evidence to confirm his theories.

H. M. Hobart: The impression I gained from conversation with him was that he could tell you not only whether the temperature correction was positive or negative but that he could state its value.

C. Fortescue: Referring to the use of an idle unit, recommended in the paper by Messrs. Johannesen and Wade, I think an idle unit is a very good thing, but there are some cases where one cannot always get an idle unit. I think the Standardization Rules ought to specify some method of determining the correct basis of air temperature without an idle unit. The idle unit can be used when one is available. It is a splendid method, but when one cannot be had and room temperatures are unsteady, there is always a tendency to a controversy between the representative of the purchaser, witnessing the test, and the man in charge of the test. One wants to take one plan of determining his room temperature, and the other wants to take another plan. Of course, the purchaser's representative usually wants to see as high a rise as he possibly can; he wants to be on the safe side, he wants to feel that he is showing up the apparatus, and naturally he looks at the figures that are higher as being correct. This paper by Johannesen and Wade shows distinctly that the highest figures are not the correct figures, and that some method of obtaining the correct figure must be indicated.

John J. Frank: Commenting on the last paper by Mr. Fortescue, and on the paper by Messrs. Johannesen and Wade, I would like to call your particular attention to the importance and necessity of recognizing the standard method of obtaining the room temperature or the temperature for correcting the rise under load or operating conditions. The use of an idle unit to determine this basis is clearly brought out by Messrs. Johannesen and Wade. It is recognized also by Mr. Eden in the paper presented by Messrs. Rice and Eden.

In the paper by Messrs. Fortescue and McConahey, no recommendations are offered, simply a reference to probable errors which might affect the test. Reference is made to the temperature rise of oil-insulated water-cooled transformers and the statement that the temperature of the air does not affect the cooling. This, of course, is not strictly correct, as the temperature of the air will affect the cooling of small units.

I would suggest that the over-potential test referred to should

be the last or final test given the apparatus. This would insure the detection of any possible defect in the transformer created by other previous tests.

J. M. Weed: I would differ from Mr. Frank in regard to using the same method for determining equivalent room temperature in all cases, that is, with all classes of apparatus. What we really wish to find is the effect of room temperature upon the apparatus that is being tested. That is, if the room temperature is not constant, we want to know what room temperature to compare the final temperature of the apparatus with. The variations in the room temperature will affect different classes of apparatus under test quite differently. For instance, in transformers we have a large body of oil which must change its temperature, due to changes of room temperature, whereas in the case of rotating machines, etc., the active materials come in direct contact with the air and are affected more quickly than the transformer, so that, although the small oil-cup might be a satisfactory method for determining the equivalent room temperature for apparatus where the active materials come in direct contact with the air, it would not be for transformers, and in order to get an estimate of the equivalent room temperature with respect to transformers we need a large body of oil which will take time to change its temperature equivalent to the time required by the transformer itself.

W. F. Dawson: I question the theory of Mr. Weed as to the rate of cooling of the transformers after the load is taken off. I have worked with approximately the same figures expressed in "amperes per sq. in.," but it would seem that he has assumed falling temperature gradient based on thermal capacity of the copper only. My experience suggests that thermal capacity of surrounding insulation material in the core and a portion of the cooling oil has also to be considered and that the falling temperaature gradient is, therefore, much less steep. The thermal capacity of copper alone is such that at an ordinary temperature, with a density of about 1100 amperes per sq. in. there will be a temperature change of one deg. cent. per min. Generally, due to added thermal capacity of insulation and other surrounding media, there will be a divisor ranging from 2 to 4, according to circumstances. For example, a transformer may be running with 2200 amperes per sq. in., but instead of four deg. cent. change per minute, there will be two deg. change or less.

C. Fortescue: I want to remark that the difference in temperature between the top and bottom oil of the idle unit, which Mr. Weed has laid some stress upon, is only a matter of perhaps two or three deg., and the error, if we take the average of the two readings as the recommended temperature, amounts only to a fraction of a degree.

J. M. Weed: Answering the question brought up by Mr. Dawson, I did not mention the calculation by the thermal capacity of the copper as a means of determining the temperature drop, but in connection with the increase in the losses during the

time that copper loss measurements were being made. The same considerations will apply, however, to the temperature drop after the load is taken off, as pointed out in one of the papers, but this calculated rate of temperature change would apply only to the first instant with accuracy. This rate will begin to change at once, so that this correction would be too large if applied to any considerable interval of time. For the first minute or two it would be approximately correct. In the heating up of the copper, the heat is all stored in the copper at the start until the copper rises in temperature, and begins to throw heat out into the surrounding insulating material and oil. Likewise, when it begins to cool, the heat is given out of the copper at a certain rate and continues to go out of the copper at that rate until the difference in the temperature between the copper and surrounding material has been reduced. Of course, that is a very short time.

In regard to Mr. Fortescue's last remarks concerning the difference in temperature between the top and the bottom of the idle transformer, I did not mean to lay stress on that consideration but was merely pointing out the possibility of not getting perfect results, but the idle transformer is so much better than any other method we have of getting an equivalent room temperature, that I have only favorable recommendations for it.

C. Fortescue: There is one point I want to bring out in connection with one of the papers in Group I, by J. J. Frank and W. O. Dwyer, entitled *The Temperature Rise of Stationary Induction Apparatus*. The paper states that if radiation is taken into account the temperature rise of the transformer instead of increasing with increased room temperature, decreases. The paper says, furthermore, that the convection introduces a factor which causes the temperature rise to tend to increase with increasing room temperature. The paper also goes on to say that the temperature gradient through the insulation introduces a factor which causes this gradient to decrease with increasing room temperature, and later on in the paper a correction is given based on the increase in viscosity of the air temperature of 0.04 of one per cent, or thereabouts, per deg. cent. to be subtracted when the room temperature is above 25 deg. cent. It appears to me that the authors of the paper have lost sight of the very points which they first bring out in their paper, namely, the fact that the cooling of such a transformer takes place in two stages; first of all, the surface of insulation is cooled by convection, so that with increase in room temperature the surface for a given pressure of air has a higher rise above the incoming air than with a lower room temperature. Secondly there is the temperature gradient through the insulation, which is a considerable part of the temperature rise in an air-blast transformer, and decreases with increasing room temperature.

In my opinion, these two factors will practically cancel each

other, and instead of a correction of 0.04 of one per cent, to be subtracted for increasing room temperature, in order to bring it down to 25 deg. cent. standard room temperature, it will be zero, or thereabouts. In fact, the correction will vary with different transformers, and a good average condition would be obtained by eliminating it entirely.

Carl J. Fechheimer (communicated after adjournment): There seems to be a tendency among the engineers who have discussed the papers, as well as among the authors, to abandon the use of a temperature coefficient, since tests which have been made indicate to some extent that the air temperature has little influence upon the final temperature of the apparatus. I do not believe this stand to be correct. It is quite evident that if the loss occurs in copper only and the current in the conductors is maintained constant, the resistance and therefore the final temperature will be influenced by the air temperature. For example, such is the case with our ordinary field coils, and I believe that for apparatus of this character the proper temperature correction should be allowed: approximately 0.4 per cent per deg. cent.

It is of importance in apparatus having copper and iron loss, on which accurate tests are desired, to determine how much of the temperature rise is due to copper loss and how much to iron loss. At one time it was believed that the temperature rise was proportional to the sum of these two losses, but this has been found to be very much in error. Mr. A. M. Gray* showed conclusively that the influence of copper loss upon temperature rise in induction motors was generally considerably more than that due to iron loss, even when the two losses were equal. The reasons therefor we shall not give at the present time. Hence, there should be a temperature correction in the case of copper loss the same as with the field coil, but it is doubtful whether there should be a temperature correction in the opposite direction in the case of iron loss, due to the fact that the eddy loss decreases with increasing temperature. This would involve so much difficulty in the determination of the relative values of hysteresis and eddy current losses that it is better to omit such a correction. Even though the exponential curve of core loss is plotted, the value of the exponent would not necessarily be a criterion of the relative values of hysteresis and eddy currents, because we have found in many cases, when plotting on logarithmic paper, core losses against voltage, below the saturation point, that the exponent was greater than 2, although we know that a considerable portion of that loss was due to hysteresis.

We can easily determine the relative values of the temperatures due to iron loss and copper loss by operating the apparatus first without load at normal voltage, so that we have little or no copper loss and normal iron loss, and then operating with full load current in the windings at considerably reduced voltage (short-

**Heating of Induction Motors*, TRANS. A.I.E.E., 1909, Vol. 28, p. 527.

circuit in the case of generators, d-c. motors or transformers; and increased slip or against rotation in the case of induction motors.) It will usually be found that the sum of the temperatures obtained by these two methods is slightly greater than the full load temperature measured under normal operating conditions.*

The statement has been made that the increment in resistance due to the higher air temperature would not generally augment the final temperatures, because more heat is dissipated by radiation at the higher temperatures in accordance with the well-known radiation law. This would undoubtedly hold if a large proportion of the heat were dissipated by radiation. We do not believe, however, that much of the heat is carried away by this means. Certainly in moving machinery the greater proportion of the heat is dissipated by convection and a negligible percentage by radiation. Even in such stationary apparatus as transformers and rheostats, most of the heat is carried away by air close to the hot exposed surfaces; this air rises and is displaced in turn by cold air which takes the place of the hot air which has risen. In this way currents of air are set up, affording excellent means of dissipation by convection. Anyone who has held his hand above a rheostat carrying current has felt the currents of hot air rising from the apparatus. We could determine experimentally how much heat we could dissipate by radiation and compare with the standard methods of combined radiation and convection by enclosing the apparatus in a chamber which is ordinarily sealed and drawing a vacuum within this chamber. If this apparatus is then operated in a normal way all of the heat will be dissipated by radiation. We could then open a door at the bottom and top of the chamber and force air at various rates through the apparatus and could then quite easily determine the relative influences of radiation and convection.

Paul MacGahan (communicated after adjournment): Referring to the question of temperature indication, it should be pointed out in connection with the "exploring coil" or "resistance thermometer" method, that in cases where a continuous indication is desired for control purposes, such as where temperature indicators are to be used on switchboard panels to regulate the loading of generators or transformers, the resistance thermometer method is generally to be preferred to any thermocouple method, for the following reasons:

1. Direct readings obtained without manipulation.
2. Actual temperature indicated instead of temperature rise.
3. Standard switchboard D'Arsonval voltmeters used instead of galvometer.

Direct readings are obtained by connecting the voltmeter according to the Wheatstone-bridge method, three arms being permanent resistors of zero temperature coefficient

*This is discussed more fully under Group III papers.

and the fourth being a search coil, wound preferably with copper. Direct current of fairly constant voltage is applied and a standard switchboard type voltmeter used in place of the usual galvanometer.

With this method, a variation of the supply voltage will cause slight errors in the indications at certain points of the scale. This can be minimized by calibrating the voltmeter with its zero torque point at the critical temperature where extreme accuracy is most desired. Thus, at this point indications would be independent of the applied voltage. At other points, there would be a slight error depending upon the variation from the zero torque point on the scale and on the variation from normal voltage. The accuracy is sufficient for all practical operating purposes but probably is not of a high enough order for testing or research work.

A notable application of this form of temperature indicator is on the N. Y. N. H. and H. single-phase locomotives, the indicators being located in the cab, directly in front of the driver's seat.

C. Fortescue (communicated after adjournment): The paper of Messrs. Johannesen and Wade calls attention to a feature of temperature determination of transformers which has always been a source of contention between the representative of the purchaser and the manufacturer. I refer to the determination of the correct temperature rise of oil-insulated transformers with fluctuating room temperature.

According to test results obtained by the authors, there is a lag of the temperature of the oil and consequently of the temperature of the coils behind the temperature of the room. It is shown that by the use of an idle unit of the same design, a base temperature is obtained from which to measure the correct rise of temperature. The temperature of the winding of the idle transformer may be used as a basis from which to measure the true temperature rise of the coils of the working transformer.

All these results may be deduced from purely theoretical considerations; thus, assuming constant emissivity of the case with varying temperatures, let

θ_1 = room temperature.
θ_2 = average temperature of oil of hot transformer.
θ_3 = average temperature of oil of idle transformer.
W = weight of oil in absolute units.
α = emissivity of case in absolute units.
γ = specific heat of oil.
S = area of case surface.
E = rate of dissipation of energy in case in absolute units.

We have therefore

Heat dissipated from case $= \alpha S (\theta_2 - \theta_1)$
Heat retained in oil $= E - \alpha S (\theta_2 - \theta_1)$

and therefore

$$\frac{d\theta_2}{dt} = \frac{E - \alpha S(\theta_2 - \theta_1)}{\gamma W}$$

or

$$\gamma W \frac{d\theta_2}{dt} + \alpha S \theta_2 = E + \alpha S \theta_1 \tag{1}$$

Consider a periodic value of θ_1 and for simplicity let us assume it to be of the form

$$\theta_1 = \theta_0 + \theta \cos c t \tag{2}$$

Then the solution of (1) gives us

$$\theta_2 = \frac{E}{\alpha S} + \theta_0 + \frac{\alpha S \theta}{\sqrt{\alpha^2 S^2 + c^2 \gamma^2 W^2}} \cos(c t - \varphi)$$

$$- \left(\frac{E}{\alpha S} + \theta_0 + \frac{\alpha S \theta}{\sqrt{\alpha^2 S^2 + c^2 \gamma^2 W^2}} \cos \varphi \right) e^{-\frac{\alpha S}{W_T} t} \tag{3}$$

where $\tan \varphi = \dfrac{c \gamma W}{\alpha S}$

The last term vanishes when t becomes infinite and at the end of a long period its effect is negligible.

The temperature condition of the idle unit is obtained by making $E = 0$ in (3). This gives

$$\theta_2 = \theta_0 + \frac{\alpha S \theta}{\sqrt{\alpha^2 S^2 + c^2 \gamma^2 W^2}} \cos(c t - \varphi)$$

$$+ \left(\theta_0 + \frac{\alpha S \theta}{\sqrt{\alpha^2 S^2 + c^2 \gamma^2 W^2}} \cos \varphi \right) e^{-\frac{\alpha S}{W_T} t} \tag{4}$$

Subtracting this from θ_2 we have

$$(\theta_2 - \theta_3) = \frac{E}{\alpha S} \left(1 - e^{-\frac{\alpha S}{W_T} t} \right) \tag{5}$$

which is also the solution for temperature rise of the transformer above a constant room temperature. It is therefore evident that the rise of the hot transformer above the idle transformer is the same as the temperature rise of the transformer under conditions of constant room temperature at every point of the temperature curve.

In addition to corroborating the results obtained by the authors, the theoretical solution clears up one point they seem to be not altogether sure of, namely the proper value of room temperature on which to base the temperature rise of the transformer when no idle transformer is available. The problem is in the case of irregular variations to a certain extent indeterminate, but the correct value may be obtained by a method of trial and error in the following manner.

Take two points on the curve of air temperature representing as nearly as possible to the eye a complete periodic variation. Obtain the average value of the room temperature between these points and draw a straight line parallel to the datum line and at a distance from it equal to the value obtained. This will intersect the curve of room temperature at three points which include between them a portion of the room temperature curve which approximates a true harmonic cycle. Proceeding as before a second average is obtained between the points on the curve indicated by the first average; repeat the process until there is no change in the position of the points obtained by the line parallel to the datum line. The last average temperature will be the true base temperature of the room between these points and the correct rise may be obtained by taking the average temperature of the oil and coils between these points and subtracting the average room temperature as obtained above.

This value of room temperature is the quantity θ_0 used in the above discussions in (3). The integral of the periodic portion through a complete cycle vanishes, so that if t be sufficiently large we have

$$(\theta_2 - \theta_0) = \frac{E}{\alpha S}$$

which is the temperature that would be obtained in the transformer with a constant room temperature equal to θ_0.

H. L. Wallau (communicated after adjournment): Table I, given in Messrs. Atkinson and Fisher's paper on "Rating of Cables," was most astonishing to the writer and does not agree with his experience.

Records kept during the last ten years on a 1,000,000-cir. mil cable operating at from 115 to 150 volts to ground, show that with the exception of the winter of 1906, when the load on this cable did not exceed 700 amperes, it has been subjected each year for a period of two to three months from 1902 to 1913 to an overload of 30 per cent for three hours, five days a week, and 20 per cent for six to seven hours one day a week, and has carried between 80 and 100 per cent of its normal load for four to five hours before the overload came on.

This feeder has been in continuous service all of the time and has given no trouble. Its insulation consists of 4/32 in. (3.1 mm.) oiled paper and it has a 1/8 in. (3.1 mm.) lead jacket.

The performance of this cable is not phenomenal, practically all of the low-tension cables on the system giving like results. These cables pass through subways containing twenty to forty similar cables operating at similar loads.

A 2200-volt, No. 4/0 B. & S. three-conductor cable 3/32 + 3/32 in. (2.3 + 2.3 mm.) insulation carried continuously for 10 hours a day an overload of 25 per cent and for 14 hours a day a load of 20 per cent of normal, for over six months, with but one breakdown during the period, and is still operating with a maximum load of 75 per cent of normal.

More caution should be exercised in overloading high-voltage cables, since the potential gradient through the insulation is not a straight line but very steep next to the conductor.

A. Herz (communicated after adjournment): I agree with Mr. Johannesen and Mr. Wade in their policy of using a mass of iron, copper and oil as reference standard for room temperatures in making heat runs on oil-insulated transformers. Such reference units should not have larger heat storage capacity than that which would follow changes in room temperatures in the course of about one hour. I mean that the time lag between a change of room temperature and that same temperature shown by means of the above temperature standard should be in the order of one hour. A small transformer would conform to this.

It has been the practise for some time in the past when specifications are drawn up for the purchase of transformers, to specify that the transformers are to be subjected to a double-voltage run at suitable frequency as one of the acceptance tests. I think there is no test which gives a person as much certainty of the condition of the insulation between individual turns in the windings and also between the separate parts of windings which are subjected to potential differences in normal operation as such an over-voltage run. I have elaborated somewhat on this and used a similar scheme in the purchase and testing of generators, in so far that a certain per cent over-voltage operation be part of the acceptance test, this to be obtained by excess excitation or by over speed run (not to exceed 15 per cent), or a combination of both. I have found no trouble in obtaining as high as 40 per cent excess voltage by such means and after such test in combination with the regular breakdown test I have felt reasonably safe in turning such apparatus over for regular operation. I have also on several occasions discovered defective insulation and coils by these means. The mere fact of applying the usual test voltages between the windings of apparatus and the ground does not put any potential difference between adjacent coils or between the individual turns or insulated joints made in assembling the winding. A generator for instance could not be tested for breakdown between phases or between coils unless all the individual coils were disconnected from each other

at the time of such test, which is usually a practical impossibility. Even then the individual turns would not be subjected to any excess voltage. I would therefore recommend that a paragraph be incorporated in the Standardization Rules to require all apparatus to be operated at excess voltage for a period of one minute. In the case of generators which are usually not subjected to excess potential stresses, such as line surges, an over-voltage run of 40 or 50 per cent would be reasonable; in transformers, as is now the practise, an over-voltage run of one hundred per cent would be reasonable; in other apparatus such excess voltages as would be deemed best by the committee.

Core temperatures, when read by a thermometer, should have such thermometer bulbs in contact with the core in such a way that there is practically no radiation from the heat-conducting medium connecting the bulb with the core. The usual method of using putty is such that the large area of putty exposed to the air puts the thermometer bulb in the presence of a medium cooler than the core, at least on one side. I think due attention should be paid to this, and when putty is used it should be covered by heat-insulating mediums, such as cotton waste. I have obtained higher temperatures than those obtained by the usual method, when covering a thermometer bulb with metal foil, this covered with a small amount of putty, and then the whole covered with a layer of waste. This high temperature was not due to local rise, because, in the cases I have in mind, the area occupied by the thermometer, covered as above, was but a fractional part of one per cent of the total area exposed to radiation.

Whenever exploring coils or thermocouples are used in proximity to coils within the electrical apparatus in order to measure temperature existing in proximity to such devices, such means of obtaining temperature should not be used unless suitable provisions are made, that in case of a breakdown between the coil or conductors and such devices, no injury will happen to the testing apparatus or the operator. The precautions are essential, since the insulation of the apparatus under temperature test was probably never subjected to such electrical stresses as it will be subjected to while under this test, and hence due caution must be used.

D. W. Roper (communicated after adjournment): The question of the limiting temperature of lead-covered cables is one of extreme interest to all users of such cable. A careful inquiry into the records and among the men actively engaged on the work of installation and maintenance of a system whose maximum load exceeds 200,000 kw. fails to disclose a single case of failure of a cable which could be definitely traced to overload. One case was found where a low-tension cable main had carried such heavy loads that the paper insulation was charred and brittle, but it was still in service, and the condition was discovered at the time that the services were transferred to a heavier cable. In other cases low-tension feeders have carried loads

far above the loads generally considered as safe for such cables and have melted the solder in the terminal lugs and in the copper sleeves connecting the sections of cable. These cables carried these excessive loads without any apparent injury, and a careful examination of sections cut from the cable after having carried these loads, failed to disclose any perceptible difference in appearance from new cable. Our experience, therefore, appears to indicate that the temperature of low-tension, paper-insulated cables is limited by other factors before we reach a temperature that will permanently injure the insulation.

With high-tension cables the behavior is somewhat different. A number of cases have occurred where cables have burned out due to local heating, as, for example, where a conduit line passed over a steam pipe, or where exhaust steam has been turned into a catch basin adjacent to a conduit line. Instances of this kind are not at all rare, and in some cases it has been necessary to re-lay a conduit line or move a steam pipe in order to avoid the frequent burn-outs of the high-tension cables at such warm locations. An inquiry among a number of the larger users of high-tension transmission cable shows that all of them have had such cables fail during, or immediately after, a particularly warm spell of weather and without any apparent cause.

A paper by Mr. Rayner in the July, 1912, number of the *Journal* of the Institution of Electrical Engineers, gives a clew to the cause of such burn-outs, and this cause is briefly touched upon by Messrs. Atkinson and Fisher in their paper, wherein they state that "the increasing dielectric loss with increasing temperature must be considered." Mr. Rayner's investigations indicate that with all types of fibrous insulation the dielectric loss increases quite rapidly with increasing temperature. It follows, therefore, that for each kind of fibrous insulation there is a temperature which may be called the "critical temperature", at which the dielectric loss is equal to the heat loss by radiation. If, therefore, the temperature of the insulation of a high-tension cable should from any cause exceed this critical temperature, then, the dielectric loss being greater than the radiation, the temperature of the insulation will continue to rise as long as the potential is applied, although the load is entirely removed. Apparently high-tension cables break down in service from this cause. The trouble does not occur on the hottest day in summer, but a day or two afterward. The cable, apparently, during the maximum load period on a hot day, reaches a temperature above the critical temperature, and then continues to increase in temperature gradually over a period of a day or two or more until it finally breaks down. While, therefore, it may not be strictly correct to state that the cables have burned out from overload, they have failed because they were allowed to exceed the critical temperature for the particular voltage at which they were operated.

So far as is known to the writer, this limiting temperature

for high-tension cables has never been determined. It probably varies with the thickness of insulation, the operating voltage and with the nature of the insulation. As near as can be judged by experience, this point is of no great consequence in cables operating at voltages under 10,000, which have the usual thickness of insulation for such voltages. The experience with cables operating at higher voltages, however, indicates that in hot weather, or where the cable is subject to heat from some external source, loads which are generally considered well within the safe capacity for such cables, will suffice to heat them beyond the limiting temperature.

It is therefore suggested that in determining the safe carrying capacity of high-tension cables, due consideration be given to the dielectric loss at the higher temperatures.

Edmund C. Stone (communicated after adjournment): It is interesting to see how much more quickly the limiting temperature is reached, and how much shorter are the periods of overload, on cables than on other kinds of electrical apparatus. The tables on pages 330–1 bring out clearly the danger to cables from even short overloads and the necessity of securing immediate relief if a cable becomes unexpectedly overloaded.

It seems to me that more information than now ordinarily obtained regarding the performance of cables would be of definite value to the users.

It is evident that, other things being equal, if one make of cable would operate safely at materially higher temperatures than others, or had heat-dissipating qualities that would permit it to carry a materially heavier load at the same temperature, that cable would be distinctly advantageous to use—indeed, would be worth more in cents per foot. If one cable had a materially higher dielectric loss, it would be distinctly more subject to breakdowns under emergency conditions of overload, for the larger the dielectric loss the more rapid the internal temperature rise under abnormal conditions; hence such cable would be distinctly disadvantageous to use. Likewise the charging current would become important if excessively large, and if any of these characteristics should change materially, it would be of great importance to the operating man to know of these changes, in order that he might adjust his conditions to suit them. For example, formerly the exciting current of a transformer could not be excessive, but recently, through the use of different qualities of steel, it has become an important factor, and it is probable that a large number of transformers have been bought with entire ignorance of the excessive exciting current that is present, to cause a reduction in the power factors of the system.

C. P. Randolph (by letter): Mr. Williamson brings out clearly several important points affecting the calculations of the temperature drop in electrical machines. I wish to emphasize some of these. It is absolutely essential in order to make accurate calculations

of this kind that there be no space filled with air between the different kinds of insulation. The air films play a very important part in the resistivity of electrical insulations where the heat flow is in a direction at right angles to the layers of insulation. On looking over the tables on thermal conductivity presented in Mr. Williamson's article, and also those measured by Symons and Walker, the most noticeable feature is the slight differences in the conductivity of the various materials. It is very likely that the resistivity is due chiefly to the number and thickness of the air films between the layers of mica, cloth, etc. Though the air films between layers are very thin, nevertheless they are present. The writer has found by measurement that the thermal conductivity of layers of mica 0.003 in. thick when under a pressure of five lb. per sq. in. is about 0.0024, whereas when the disks are loosely piled on each other (under a pressure of perhaps one-fourth lb. per sq. in.) the thermal conductivity is 0.00090* or about one-third of the former figure. The conductivity of a pile of mica sheets will increase with the pressure very rapidly at first, but very slowly when the pressure has passed such a value that the air films are nearly absent. This pressure is always exceeded in properly assembled coils when they are firmly imbedded in the slots, so that one should be able to calculate the temperature difference between the copper and the iron with a degree of accuracy sufficiently high for practical purposes. The temperature coefficient of the thermal conductivity of layers of mica when tightly pressed is very small, and when loosely pressed it is very high.

Problems involving the calculation of heat losses are always very complex even in carefully designed laboratory apparatus, and the calculation of the temperature at many points in a generator or motor under different operating conditions presents problems so complex that they are often practically impossible of solution. Fortunately the designer wishes to know the temperature only at the places where it is highest and often the problem can be so simplified without impairing the accuracy that the necessary calculations are comparatively simple. Mr. Williamson shows clearly how to handle one of a number of such problems that arise. There are no engineering problems that require the exercise of "good judgment" to arrive at results of value, so much as those involving the flow of heat. Practically every problem requires that some assumptions be made, as otherwise the calculation would be too complex to handle. The simplifying assumptions may allow problems that at first appear to be impossible of solution finally to be solved accurately and easily. At the same time these assumptions may lead easily to results 100 per cent in error, if "good judgment" is not exercised. Experience in dealing with problems of heat flow is necessary to obtain correct results. When a problem is so complex that

*The thermal conductivity is given in watts per degree centigrade per inch cube.

one cannot be sure of the accuracy of the calculations the result may be merely used to locate places of high temperature. Then temperature coils may be inserted at these points to determine the actual temperatures.

The designing engineer should have at his command accurate data as to the life at different temperatures of the various insulations, so that each material can be used under the temperature conditions to which it is most suited. Data on this point are needed now more than data on thermal resistivity. Such data are very difficult to determine experimentally, but without them we must use relatively high—and therefore expensive—factors of safety.

It is the actual temperature of the insulation, and not the temperature rise, which limits the output of a machine, as has been brought out in several papers presented at this meeting of the Institute. This depends not only on the temperature of the surroundings, but also on the conductivity of the insulating materials, iron, etc., and on the surface properties of the machine. For instance, to test a machine before it is painted may lead to erroneous results. Painting usually increases the emissivity, thereby making the machine run cooler than previously. Reliable data on this point are very meager, but the writer is at present carrying out some experiments to clear it up.

E. D. Edmonston (by letter): Messrs. Atkinson and Fisher have given engineers and users of cables much valuable and needed information. There has been a dearth of information on underground electric cables, and for much of the published data we have had in the past, we are indebted to Mr. Fisher and his company.

We have been given the maximum temperature limits of safe practise in working cables, but we are not as yet in possession of enough data to predetermine fairly accurately the current rating of an electric cable for service underground in various conduit formations, in various soils, under varying conditions.

The formulas given, as stated, are based upon experiments on the rise in temperature of cables in free air, whereas most of our lead-covered cables for power and lighting service are placed underground in conduit constructions where there is little appreciable circulation of air through the ducts.

From the formulas given we may compute the temperature rise of copper above lead, and the rise of lead above immediate surroundings; but in the rise of temperature of surroundings due to the presence of other cables and the nature of the surroundings, we have only meager and limited data available on which to base a guess in many of our calculations. Yet, as the paper states, heating and current rating of any given cable may be reduced to a half or a small fraction of its normal rating, due to the extreme variability of the external conditions. For underground cable work, therefore, to make the fullest use of the valuable information given in this paper, we should endeavor to obtain more infor-

mation than has been published concerning the conduction of heat by the earth, when conduit lines are laid in clay, loam, sandy soil, etc., both when the soil is damp and when dry. In the usual subway construction, with manhole spacings of 200, 300 or 400 ft. I believe that there is little dissipation of the heat generated in cables through possible circulation of air in conduits, but I would like to obtain the views of others on this matter.

Turning for a few moments from the subject of cable heating from the conductors, to the heating of cables from without, you may be interested in some findings in Baltimore where we have nearly a half-million feet of several different makes of 13,200-volt transmission cables in the lighting and power company's service, installed over a period of about nine years. Some of these cables which had been in regular service for some years began to cause us trouble for the first time last summer. In a conduit line where we had twelve transmission cables, we had a cable breakdown between manholes in one section. This was followed about a week later by the breaking down of another cable at the same point in the conduit line, but of course in another tile duct. A week or so later another cable broke down at the same point in the conduit line, and so on until we had lost five cables. The cables in question were three-conductor, 4/0 B. & S. gage, 6/32 in. by 6/32 in. paper by 5/32 in. lead sheath; and the breakdowns occurred between conductors. A short time after the initial breakdown, we had a breakdown of a cable between manholes in another section of the conduit line, which was followed after short intervals of time by four additional breakdowns at about the same point in the conduit line in nearby ducts. We dug around and exposed the conduit line at the points of trouble, examined the conduit construction, examined the adjacent cables for signs of electrolysis, and found nothing unusual in the nature of the soil. All of the cables have been working well under normal rating, and the maximum temperature we were able to get between manholes in the duct line was about 52 deg. cent. by recording thermometers. We sought to find some electrical phenomena to account for the trouble, and failing in this I took our troubles to our chemists. Moisture was found to exist in quite considerable quantities in the paper insulation. Many samples of cable, and also some new cable, were carefully taken, from all of which we were able to distill (using a temperature under 120 deg. cent. with a vacuum of approximately 26 in.) from 1 to 2 grams of water per 5-in. length, which is equivalent to about 1 to 2 ounces of water per 10-ft. length of cable. We cannot account for the cause of initial breakdowns mentioned; but we feel satisfied that the succeeding breakdowns at the same points in the conduit line were caused by the localized heat from the first short-circuit vaporizing the moisture held by capillarity in the paper insulation of the adjacent cables, which vapor, driven back in the cables from the hottest point, distilled in globules of water at a nearby

point where the cable was sufficiently cool to condense the vapor; and these globules of water so formed, did the rest after a period of time. All of the cables affected were ordered under the American Standard General Cable Specifications covering paper-insulated lead-covered cables prepared by the Paper Insulated Power Cable Engineers' Association, were tested at factory and after installation, and complied fully with the specifications. Replacement of the damaged sections of cable by the manufacturer, under a five year guarantee, does not compensate for the loss of prestige and service due to the interruptions caused by the cable breakdowns.

The point I wish to make, is that we have not a standard cable specification which will adequately protect the purchasers and users of cables, especially high-tension cables for underground service. I have appealed to three of the large cable manufacturers to tell me the limitations of moisture which they could assure in a specified make-up of cable; but in each case their answers have given me to believe that they had little knowledge of how complete their vacuum process was in extracting the moisture from the paper before applying the compound and sheathing; and this has led me to draw up my own specifications for the limitations of moisture.

Mr. Fisher, in a previous paper before the Institute, stated that it was to be regretted that the manufacturers and operators of electric wires and cables in this country did not draw up a reasonable set of specifications, because it would simplify matters for consulting engineers, operating companies and manufacturers. We are all striving for standardization, and I beg to suggest that the work of formulating an adequate set of cable specifications could well be taken up by the Institute and would bear good fruit for both the users of cable and the manufacturers.

In some of the big cities, millions upon millions of dollars are invested in undergound electric cables. The valuation of the underground cables in our little power and lighting system in Baltimore totals an amount in the seven figures, and approximates the total cost of all the electrical equipment in our stations; yet with some lighting companies where greater portions of their distributing systems are underground, the cost of underground cables probably exceeds the total investment in all station equipment. With such amounts involved, the operating companies are naturally most desirous of obtaining cables of the best design and construction at a fair cost, and of knowing how to work those cables to the best advantage underground in properly designed conduit construction. Reports by a number of the large lighting companies made last year to the National Electric Light Association Committee on Underground Construction, give evidence concerning high-tension cable breakdowns which indicates that there is yet much to be desired in the make-up of, at least, high-tension cables; which weaknesses in construction have not been shown by the initial tests that

it has heretofore been customary to apply. Many cable users say, with much logic, "leave the make-up of cables to the manufacturer," but on high-tension paper cables the manufacturers appear not all in accord. True, many of them appear to use much the same cable compound, principally resin oil, under different trade names. The papers used appear not to be very different in character, though the quality may differ somewhat; but the thickness of the paper and the tightness of the wrapping varies considerably for high-tension cables. Some manufacturers recommend a loosely wrapped high-tension cable, others, a tightly wrapped cable. Each has certain advantages, but on account of the paper costing considerably more than the compound used, is there a temptation for the manufacturers to use a loose wrapping, though the tight wrapping may be desirable? The Institute affords a common ground for cable manufacturing engineers, and engineers of cable users, to get together in an endeavor to formulate more adequate specifications than we have yet had, and give to the profession at large recommendations which would be of tremendous value and in line with standardization. I venture to hope that an Institute Committee will take up this work.

A communication first presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912, and discussed at the Midwinter Convention, New York, February 27, 1913.

Copyright 1912. By A. I. E. E.

THE MYRIAWATT

BY H. G. STOTT AND HAYLETT O'NEILL

The object of this communication is to introduce a new unit of power which, if adopted, will afford a basis of comparison of all converters of energy, thermal and mechanical; and also will be international in its character, as it is merely a new multiple of the watt.

In American and European practise, at the present time, there are in use many empirical units, the use of any one of which is restricted to a distinct territory. A few of the more important ones are, horse power, boiler horse power, kilowatt, cheval à vapeur, pferde-kraft and poncelet. Obviously an engineer, in attempting to compare data from a foreign country, is compelled to face a confusion of terms, which usually can be made intelligible only by laborious calculations.

Again, in the United States there are in vogue such units as boiler horse power and horse power, which, while similar in sound, have no logical connection; and one has yet to find where the "horse" comes in.

With the rapid development in electrical measuring instruments, and, until recently, a corresponding lack of development in steam-flow measuring instruments, the term kilowatt has become more and more used as the one unit of power output.

The term became a necessity with the growing favor of steam turbines, and all direct-connected units where it is impossible to measure accurately the mechanical and the electrical power separately.

To form a connection between the boiler or producer output, the engine and generator output, the term "myriawatt"—

derived from the Greek "myria," meaning ten thousand, and the term watt—is proposed.

For the purpose of standardization, the British thermal unit, 1/180 of the heat required to raise one pound of water from 32 deg. fahr. to 212 deg. fahr. and the equivalent evaporation from and at 212 deg. fahr. (970.4 B.t.u.) is used (Marks and Davis).

From this, the following equivalents are obtained:

1 Foot-pound	=	0.0012861	B.t.u.
1 Kilogram-meter	=	0.009302	B.t.u.
1 Gram-calorie	=	0.0039683	B.t.u.
1 Horsepower	=	2,547	B.t.u. per hr.
1 Cheval à vapeur	=	2,512	B.t.u. per hr.
1 Pferde-kraft	=	2,512	B.t.u. per hr.
1 Poncelet	=	3,349	B.t.u. per hr.
1 Kilowatt	=	3,415	B.t.u. per hr.
1 Boiler h.p.	=	33,479	B.t.u. per hr.
1 Myriawatt	=	34,150	B.t.u. per hr.

Reduction of the Myriawatt to the above units.

1 Mw.	=	34,150	B.t.u. per hr.
1 Mw.	=	8,605,000	Gram-calories per hr.
1 Mw.	=	26,552,000	Foot-pounds per hr.
1 Mw.	=	3,670,900	Kilogram-meters per hr.
1 Mw.	=	13.410	Horse power.
1 Mw.	=	13.597	Cheval à vapeur.
1 Mw.	=	13.597	Pferde-kraft
1 Mw.	=	10.197	Poncelets.
1 Mw.	=	10	Kilowatts.
1 Mw.	=	1.020	Boiler horse power

Reduction of all of the above units to Myriawatts or Myriawatt-hr.

1 B.t.u.	=	2.928×10^{-5}	Mw-hr.
1 Gram-calorie	=	1.1621×10^{-7}	Mw-hr.
1 Foot-pound	=	3.7662×10^{-8}	Mw-hr.
1 Kilogram-meter	=	2.7238×10^{-7}	Mw-hr.
1 Horse power	=	7.457×10^{-2}	Mw.
1 Cheval à Vapeur	=	7.354×10^{-2}	Mw.
1 Pferde-kraft	=	7.354×10^{-2}	Mw.
1 Poncelet	=	9.807×10^{-2}	Mw.
1 Kilowatt	=	1.00000×10^{-1}	Mw.
1 Boiler horse power	=	9.804×10^{-1}	Mw.

The last two are practically the same, differing by only two per cent. The usual practise is to rate water-tube boilers on the basis of one boiler horse power per 10 square feet of heating surface.

With modern plants, notably those in marine service, operating at from two to five times this rating, the ordinary method of

determining nominal boiler capacity could be stretched 2 per cent without materially affecting the present rating: *i.e.*, the boiler might be rated at 34,150 B.t.u. per hour for each 10 square feet of heating surface, instead of at 33,479 B.t.u. per hour for each 10 square feet of heating surface.

The myriawatt as a unit of boiler or producer output, and correspondingly a unit of input to all kinds of dynamical machinery, is fixed in value by the watt, and by its very sound gives a clue to its meaning.

To compare efficiencies of direct-connected units and eliminate the various factors of quality of steam, pressure and vacuum, the term "B.t.u. per kilowatt-hour" has been used. If we use the term myriawatt,

$$\text{per cent overall efficiency} = \frac{10 \times \text{kilowatts output}}{\text{myriawatts input}}$$

Also, with the thermal efficiency of the engine known, the heating surface in the boiler room is determined (assuming the 10 square feet rule), two kilowatts per myriawatt input to an engine is equivalent to 20 per cent thermal efficiency of the engine and the heating surface in the boiler room equals kilowatts engine output $\times$ 10/2.

Obtaining an exact figure of the same with the boiler horse power unit involves a tedious operation.

The efficiency of internal combustion engine-driven units of all cycles, such as Diesel, Brayton, Otto, etc., is determined by rating the heating value of the fuel in myriawatts; thus,

$$\text{per cent efficiency} = 10 \times \frac{\text{kilowatts output}}{\text{myriawatts input}}$$

With hydraulic machinery, again rating the water power input to the wheels in myriawatts:

$$\text{per cent efficiency} = 10 \times \frac{\text{kilowatts output}}{\text{myriawatts input}}$$

Thus, in the term myriawatt lies a simple, logical and universal means of comparing outputs and inputs of all classes of energy converters, the meaning of which will be clear to all engineers wherever a piece of electrical machinery is to be found.

COMPARISONS IN EFFICIENCIES AND RATES OF OUTPUT WITH VARIOUS TYPES OF ENERGY CONVERTERS, IN TERMS OF THE MYRIAWATT

1. Boiler output:

Nominal rating = 600 boiler h.p.

Total draft head inches water gage	Boiler h.p.	Myriawatts
1.730	1375	1348

2. 5000-kw. engine:

Kw. output	Lb. steam / kw-hr.	B. t. u. / kw-hr.	Kw. output / Mw. input	Per cent thermal efficiency over-all
4977	17.2	20,160	1.70	17

3. 5500 kw. high-pressure turbine:

Kw. output	Lb. steam / Kw-hr.	B. t. u. / Kw-hr.	Kw. output / Mw. input	Per cent thermal efficiency over-all
8183	16.39	18,450	1.85	18.5

4. 15,000-kw. engine—low-pressure turbine.

Kw. output	Lb. steam / Kw-hr.	B. t. u. / Kw-hr.	Kw. output / Mw. input	Per cent thermal efficiency over-all
11,240	13.19	15,660	2.18	21.8

5. 56-in. low head water-turbine:

Brake h.p.	Brake kw.	Kw. output / Mw. input	Conversion eff. per cent over-all
283	211	8.41	84.1

6. Steam plant efficiency:

Lb. coal per kw-hr.	=	2
B.t.u. per lb. coal	=	14,250
B.t.u. per kw-hr.	=	28,500
Kilowatts per myriawatt input to boilers	=	1.2
Plant efficiency	=	12 per cent.

7. Gas power plant efficiency:

Kw. output	Cu. ft. gas / Kw-hr.	B. t. u. / Kw-hr.	Kw. output / Mw. input.	Per cent thermal efficiency overall
5200	145	14,220	2.4	24

DISCUSSION ON "THE MYRIAWATT" (STOTT AND O'NEILL), NEW YORK, FEBRUARY 27, 1913.

H. G. Stott: A great deal of criticism has been made of this paper, which was presented at the convention held in Boston last June. The greater part of this criticism, I think, is entirely due to a misconception. The misconception is that we are endeavoring to introduce a new unit. A little careful consideration of the paper would show that that conception is entirely wrong. All that was attempted to be done was to get in the thin end of the wedge, as it were, of the metric system into our measurements of mechanical power. We all know how we suffer at the present time from the numerous illogical and irrational units which are used in calculations on thermodynamics and mechanical units of power. For example, we have the boiler h.p., which was originally meant to mean that the boiler could evaporate 30 lb. of water from a temperature of 100 deg. to steam at 70 lb. Now latterly it has been modified to mean the amount of heat required to evaporate 34.5 lb. of water at a temperature of 212 deg. fahr. This is purely arbitrary, and has no scientific or rational basis.

There is still another boiler h.p., and that is one which simply means it is equal to 10 sq. ft. of heating surface in the boiler. The h.p. is sometimes used in the sense of being shaft h.p., sometimes brake h.p., and also for the indicated h.p. of an engine.

There are at least half a dozen different values attached to this term of horse power, and it seems to me that it is a happy coincidence that 10 kw. are just about equal to one boiler h.p., that is, within two per cent of it. The line of least resistance is always the best one to adopt in trying to introduce the metric system to those who have been accustomed to the abominable English system of units, and that is the basis of our attempt.

There has been a great deal of criticism directed against the unit which we propose. The first one is, why not use the kw. at once? The trouble with that is that you immediately have to introduce the factor of 10; say that 10 kw. are equal to 1 boiler h.p., which is approximately true. Then there is the difficulty in nomenclature, in referring to the fact that you require 10 kw. to deliver one kw. at the switchboard. Now, it seemed to us to be a little simpler to use the prefix "myria", meaning 10,000. The precedent for that is that in the metric tables we have the millimeter, the centimeter, the decimeter, the meter, the dekameter, the hectometer, the kilometer, and the myriameter.

Now, the same thing is true with the gram. We find there the myriagram also. So that there is absolutely nothing new about it, and we simply apply the well-known prefix of "myria" to the watt. The kilowatt is not the unit, the watt is the unit. We have not introduced a new unit, but have used a prefix well known in Continental practise, the prefix "myria" to indicate

10,000 times. Now, the whole object of this little paper, the idea of introducing the myriawatt, as I have said before, was to begin gradually, from the easiest point of attack, the introduction of the metric system into mechanical and thermodynamic calculations. The introduction of such a unit, it seems to me, will help a great deal, because naturally the next step, for example, in calculations on steam, will be the use of the centigrade thermometer scale. We are all familiar with that in electrical work. With the fahrenheit scale in calculations on thermodynamics, you are continually troubled with the plus or minus 32 deg. and it is a constant source of error.

With the centigrade scale, that is eliminated, so that the next step I hope to see introduced is the abandonment of the fahrenheit scale and the introduction of the centigrade scale for all thermodynamic work involving calculations. These things are all time-savers, just as the entire metric system is a time-saver over the old English system of units.

There is another reason for the introduction of this term. It has heretofore been the custom to specify the performance of a steam unit in pounds of steam. That was a perfectly legitimate and a perfectly safe way of expressing it, as long as there was no superheat, and as long as you worked to constant vacuum, for the vacuum varied but slightly from twenty-six inches as the standard. But nowadays, when we are going to 28½, 28¾, 29 and 29¼ inches actual vacuum in guarantees, when referred to 30 in. barometer, and when the superheat may vary from 100 deg. to 200 deg., the pounds of steam per kw-hour mean nothing; you must get down to thermal units. The transformation from the thermal basis of the B.t.u., or the calories, is very simple, and is given in that little paper, so that we would naturally expect that, in expressing it in myriawatts, the conversion into the thermal units is implied, because that is a very simple matter by the use of a steam table.

The question of getting steam tables which are required in the metric system, is also now being taken up, and the authors of the tables best known today, have agreed that if the metric system of units in thermodynamics is adopted they will have their tables translated into the metric system.

Electrical engineering and mechanical engineering are now so closely allied and actually connected by the steam turbine that it is impossible to determine the efficiency of one without the other. There is no way I know of, of separating the losses in the turbine and in the generator. That comes in as an appropriate part of this matter, so that the electrical engineer is as much interested in this subject, in my opinion, as the mechanical engineer, and therefore I think if we do all we can to assist in the adoption of the metric system in all tests and guarantees, the rest of it will come very quickly. It is a very simple matter, all we have to do is to introduce the centigrade thermometer, and then the only quantity we have to translate will be pounds of water into kilograms. Then we will have our

tests, reports and guarantees on precisely the same basis as they have in Europe; in other words, we will have our results in international units. At the present time, if we take up the results of tests on the steam turbine units which are practically the only sources of power in large stations now, we find that it is impossible, at first sight, to compare the European results with our own results. We have to sit down and go over a series of laborious calculations.

Now, if we become accustomed to the calorie, kilogram and the centigrade scale, which all electrical and chemical engineers are using, it would be a very simple thing to work out all our tests and all our guarantees in the metric system of units.

C. P. Steinmetz: If you want to realize the importance of getting to an intelligible system of nomenclature, you only need to consider a sentence like this: To operate ten 300-ton trains per day, at 40 miles per hour, with an acceleration of 0.5 mile per hour per second, two 2000-kw. turbo-alternators are installed. The periodicity of these generators is 25 cycles per second; they are designed for a temperature rise of 40 deg. cent. Their speed is 1500 rev. per min. and they are cooled by the circulation through each of them of 10,000 cubic feet of air per minute. This circulation is maintained by a pressure of 1.5 inches. Their consumption is 11 lb. of steam per kw-hr. at 175 lb. boiler pressure and 75 deg. fahr. superheat, and a 28-in. vacuum. Steam is supplied by six 300-h.p. boilers, consuming 2 lb. of coal per boiler h.p. The coal has a thermal value of 14,000 B.t.u. per pound. 1000 gallons of condensing water per minute are required at full load.

Now, pick out the number of heterogeneous, incompatible and erratic units in that brief statement, and then imagine how any sensible engineer can really maintain that such a system of units does not constitute a terrible and foolish handicap to progress in engineering.

Comfort A. Adams: It seems to me a crime, that men who call themselves engineers, who talk much about efficiency in the machines they develop, will continue to encourage the perfectly inhuman and wasteful system of units so aptly described by Dr. Steinmetz, when its use involves a loss in efficiency on the part of every one of us, of every man who has anything to do with engineering, which is almost incredible. I believe it is a conservative statement that the average engineer wastes a working year of his life by the use of our messy system of units. Frequently a student of limited capacity will fail to grasp the real physical significance of a problem, because of the confusion of units.

The myriawatt is only a step, but in the right direction. We are fortunate in having such a good representative as Mr. Stott in the American Society of Mechanical Engineers. He should certainly have the vigorous support of every electrical engineer.

Leo Schuler: I have learned with great pleasure that the European engineers are working at about 2.5 per

cent greater efficiency than you do, and I do not think that I need say anything additional to what has been said in favor of the introduction of the metric system in engineering work in the United States. Nevertheless, I would not propose that you begin this reformation by the introduction of another new unit, the myriawatt, as proposed. The kilowatt is such a well-known unit already, even here in America, that I think confusion would be increased by another word, the myriawatt; I must also say that Mr. Stott is mistaken if he thinks that the prefix "myria" is very well known in Europe. As a matter of fact, it is not. Nobody uses it as a prefix, neither for myriameter or anything else. I think it would be better to say 10 kilowatts instead of one myriawatt.

In regard to the introduction of the kilowatt as a mechanical unit, that is making good headway and the Society which I represent here at this meeting, the Verband Deutscher Elektrotechniker, has already decided to rate electric motors in kilowatts, beginning January 1, 1914. It was arranged to give the manufacturers about two years' time for changing their nameplates and types. They could not rate a one-h.p. motor at 0.746 kilowatts but they must have it in round figures. There has been practically no difficulty in introducing the kilowatt by the Verein Deutscher Ingenieure, and the proposed new expression, the "neupferd", or in English, the "new horse," has been proposed, not by the mechanical engineers but by the electrical engineers, to facilitate its introduction by the mechanical engineers; the mechanical engineers, however, say that they do not want it, that they can understand "kilowatt" well enough.

H. M. Hobart: It has been my experience that here in America the 2000-lb. ton is the chief stumbling block to the introduction of the metric system. The other stumbling blocks to which Mr. Stott and Dr. Steinmetz have alluded are serious, but the 2000-lb. ton is the chief difficulty. There is not much good to be accomplished in getting people to change pounds into kilograms, if you are going to have the irrational relation between the kilogram and the ton, yet you will rarely find an American engineer who will countenance any notion that there can be anything better than the American ton. In this matter of the 2000-lb. ton, America stands alone. The 2000-lb. ton is never used by engineers in the British Empire. If in England it is said that the weight of anything is 100 tons it is taken as a matter of course to mean 100 tons of 2240 pounds. The English ton is 2240 pounds. The metric ton is equal to 2204 pounds, but the difference of only about one per cent is so small that it would not affect one engineering calculation in a thousand. If you can accustom people to speak in tons, you have a common bond between the metric system and the English system, and the way is smoothed for introducing the kilogram, which for all practical purposes is the one-thousandth part of the English ton. This is the connecting link which is not available in America, and in my opinion

it is to a considerable extent for this reason that the metric system is used far more extensively in England than in America. America is away behind in the introduction of the metric system. Some six or eight years ago I worked out a set of steam tables, at a tremendous expenditure of labor, in which I gave the energy in kw-hr. per ton of steam for all temperatures and pressures, and with vertical columns for various degrees of superheat —no superheat, 50 deg. superheat, 100 deg. superheat, and so on, and I published these tables in a book entitled "Heavy Electrical Engineering." I do not believe these are yet used by anyone except myself. I am pleased to hear the proposal by Mr. Stott that tables of this kind should be employed. They are already available in the book to which I have alluded.

Charles P. Steinmetz: I entirely agree with Professor Adams that it is a crime for mechanical engineers to hold on to a mis-system of units, but I know of a greater crime still, and that is that men who do not have to deal with factory foremen or boiler testers or other people of limited horizons of intelligence, incapable of understanding anything new,—that men who are working, not for today, but for future generations, that is, very many educators throughout our educational institutions, our colleges and universities, in the electrical engineering departments, teach the English system with its inches, pounds, and gallons, its British thermal units and its fahrenheit degrees, first, because they desire to pose as practical men and secondly because they are too inveterately lazy to do anything but drift.

Now, there is where we can do more good than anywhere else, by *really giving the instruction* in the metric system. It would materially increase the efficiency of the work of these sound engineers to impart the metric system to them. You cannot transfer quickly from anything to anything else, say from an electrical phenomenon to a thermal phenomenon, without running the chance of being hopelessly mixed up, by the use of the English system, and you need the metric system to assist you.

I believe what ought to be done is that universities and colleges should teach, not simply and purely the metric system, but they should very thoroughly teach the method of reduction from the English to the metric, and from the metric to the English system, and educate the new generation to do all calculating work in the metric system, and to transform given data, which are in the English system, into the metric system, make calculations in the metric system, and retransform the results back from the metric system into the English system. This gives a much higher degree of reliability to the calculation, because it eliminates the enormous possibility of making a mistake in the irregular, irrational reduction factors, in using thermal units, and foot-pounds and kilowatts, and boiler horse power, and any one of the twenty-five different units for the same quantity.

I was very badly mixed up in my last attempt at using the English system, and I found it necessary to transform all the data procured from the English system, into the metric system,

do all the calculating metrically, and transform the results back. It is much more efficient to do this.

After all, what we want to do in educating young engineers is to educate them to do the work efficiently. The most efficient way, naturally, is by the exclusive use of the metric system, but as long as the practical men are always lagging one or two generations behind the world, and they are still using the English system, the next efficient way would be to do all the work in the metric system and transform from the English to the metric, and from the metric back to the English, in using the terms and giving the results.

B. G. Lamme: I am fully in accord with any move to rate motors in kilowatts, instead of horse power. There is one fortunate thing, with our present mixed system, which will help us in making this change. We have been rating apparatus largely in halves, quarters and eighths, instead of in decimals of horse power, and the relation between the kilowatt and horse power is practically three-fourths, so that in a great many cases, in changing from horse power rating to the kilowatt, we do not obtain any particularly odd ratings. For instance, 50 h.p. would be changed to 37.5 kw., which is at present in common use in generating apparatus. One h.p. would mean 0.75 kw. We would therefore be able to change to the kilowatt rating with very little confusion.

James Burke: I think there is considerable advantage, sometimes, in having both systems—it sometimes gives us a chance to think what we are going to say in answer to a question, while we are apparently taking time to convert from one system to the other. There is also a certain romantic influence in maintaining some of the old units. I come from a part of the country where we still talk of "two bits" instead of twenty-five cents.

I would ask Mr. Schuler if it is not true that in Germany they still use the 60 seconds for a minute and 60 minutes for an hour. In this country the decimal hour has come largely into use in manufacturing, and time records in manufacture are kept in decimal parts of the hour. I would also like to ask Mr. Schuler if it is not true that in Germany the English system of threads on bolts, nuts and screws is still the commercial system, rather than the metric system.

Leo Schuler: Of course, Mr. Burke knows that it is so, and he need not ask.

I would say, in reply to what Mr. Lamme said, that the time lost is not only in making the transformation, but you have to transform from one kind of unit to another kind of unit in your calculations. For instance, when you wish to calculate the energy stored in a moving mass, if the mass is given in kilograms and the speed in meters per second, then the fraction $\frac{m v^2}{2}$ equals watt-seconds.

A. E. Kennelly: How far are they using the metric system in screw threads in Germany?

Leo Schuler: Metric screws are used for small apparatus only. For machinery screws, generally the Whitworth system is used.

L. W. Chubb: In expressing any physical quantity it is better to follow the most common custom. In speaking of power it is customary to speak of watts when below 1000 and kilowatts above this figure. A 20-megawatt generator was mentioned yesterday, but such an expression of rating is uncommon.

The most familiar and desirable prefixes are limited to every third digit and every third decimal place. "Kilo," "mega", "milli" and "micro" are common and desirable. Deka, hecto, myria, deci, centi, are uncommon, except in the case of centimeter, which in reality is the working unit, and one of the three fundamental metric units.

What is wanted is standardization and not deception. The myriawatt seems to have no advantage except to deceive the uninitiated regarding the efficiency of the mechanical end.

Charles P. Steinmetz: I do not agree as to the difficulty of introducing the myriawatt. I think it would be difficult to introduce the kilowatt in this connection, for two reasons; first, it means a rise of 10 points, that is, where the practical man would speak of a 100-h.p. boiler, it would be necessary to speak of a 1000-kw. boiler, and that is beyond the mental capacity of the users of the English system. We must consider that we are not all engineers, but that the majority of the people who are using the English system are working men, and factory foremen, etc., and that must be considered, and it would be a hardship to have everything increased in numerical value by ten-fold. Under the plan which we are now considering, in order to supply steam to a 100-kw. generator, a 1000-kw. boiler would be required, and that would be a difficult designation to bring about amongst the less-educated people. Moreover, the educated mechanical engineers would also rather resent the adoption of a nomenclature which would disclose the low efficiency of mechanical and thermodynamic transformations.

After all, we have to realize that the persistent adherence to the English system by mechanical engineers is not altogether conservative, but there is also a rather mixed feeling, not to say consciousness, the feeling that if they go to a system of units based upon the metric system it does not look well. It does not look bad to say you use so many pounds of coal per B.t.u., and that there are so many B.t.u's. in a certain number of kilowatt-hours, but it does look bad to say that you use 15 joules of coal to produce 10 joules of steam energy, and that 10 joules of steam energy are required to supply 1 joule of electrical energy. The metric system shows up the efficiency of transformation.

We have nothing to be ashamed of as electrical engineers, but the mechanical engineers are faced by the inherently low efficiency of mechanical and thermodynamic transformations, and they do not care to flaunt these low efficiencies too much before the public.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

INDUCTION MOTOR LOAD LOSSES

BY HENRY G. REIST AND A. E. AVERRETT

The question of load losses on induction motors frequently comes up when the various methods of testing are discussed.

It is usually more desirable to measure the losses and thus obtain indirectly the efficiency, than to obtain it from a direct input and output test, because a variation of two or three per cent in the losses will affect the efficiency results only slightly, while on direct measurement the error would be large.

Commercial circuits are, as a rule, more or less unsteady, both voltage and frequency changing, dependent upon the load; as both efficiency and power factor largely depend on the constancy of conditions, it is desirable to eliminate methods which require laboratory conditions to insure accuracy.

On large machines it is almost impossible to take direct measurements, on account of limited power. Therefore, some method of determining the efficiency by losses is imperative.

The losses usually measured are core losses, friction and windage, primary and secondary I^2R losses. See A. I. E. E. Standardization Rules, sections 162-167. Core loss is usually nearly constant, but under certain conditions may increase with the load and materially reduce the efficiency.

The customary method of obtaining the core losses is to run the machine without belt at gradually reduced voltage until it breaks down, reading both watts and amperes; curves of these values are plotted, and the point where the watt curve extended passes through the ordinate at zero voltage is taken as friction.

The I^2R at normal voltage is subtracted and the remainder is taken as core loss.

Primary I^2R is directly obtainable; the secondary, when of a definite phase-wound type, is also directly secured, but when a squirrel cage type, it must be obtained by indirect methods, and is approximately proportional to the slip.

Load Losses

Under certain conditions the core loss and I^2R are materially increased.

When saturation occurs in the iron, due to the load current, the core loss may be increased on account of a changed flux distribution. This is especially noticeable in motors with completely closed slots, that is, with a thin iron bridge across what would normally be the slot opening.

Such motors do not have a constant reactance or core loss, but both change with load, due to the saturation in the thin iron parts—the core loss increasing and the reactance decreasing. Under these conditions the only correct method of obtaining the efficiency is by an input-output test. The amperes at short circuit, with the rotor blocked, increase more rapidly than the voltage, whereas a motor without saturation will show amperes proportional to the voltage.

Nearly all motors, however, will show some saturation in the blocked condition when several times full load current passes, and a constant core loss should be assumed only through the range of short-circuited current where the amperes are proportional to the voltage.

Copper Losses

The copper losses are also subject to correction. Eddy currents will appear wherever heavy conductors are used. These eddy losses are shown by the wattmeter readings taken with the rotor blocked. Those chargeable to the stator are additional to the primary I^2R from measured resistance; those belonging to the rotor or secondary practically disappear under load conditions, due to the low frequency of slip.

In order to separate these, the rotor can be removed and a stator test made with amperes and watts; if there are no eddies the I^2R and measured watts will agree, but if not, the excess watts will represent additional losses which appear under load, and can be represented by an effective resistance.

Tests have been made which verify the above statements; round wires or rectangular strips of one cm. or less for a maximum dimension, apparently do not show any appreciable loss at

60 ~ or less; this maximum dimension, however, should be further studied, as sufficient tests have not been made to give the maximum limit. Certain deep bar-wound stators, however, have shown losses up to five or six times the losses due to I^2R alone.

Deep bar secondaries show a large eddy loss at standstill, which practically disappears at slip frequency, but the reduction in eddies at slip is partially made up by an increase in reactance and, therefore, a reduction in power factor; there seems no easy way at present to determine this effect, except by an input-output test.

Core Losses

Tests were made on a machine with completely closed stator slots, having a web 0.03 in. (0.76 mm.) thick, and repeated on the same stator having a 1/16-in. (1.58 mm.) and also a ⅛-in. (3.17 mm.) opening, the same rotor being used in each case, it having 1/16-in. (1.58 mm.) opening. The primary had 72 slots and the secondary 47 slots. The following are the results:

Completely closed			1/16-in. opening		1/8-in. opening	
Voltage	Watts	Amperes	Watts	Amperes	Watts	Amperes
110	52	3.62	51	3.9	54	4
220 (normal)	224	6.55	202	7.2	208	7.6
300	390	9.25	328	9.85	350	10.5

As there were eight conductors, it will be noticed that the ampere conductors per slot are low.

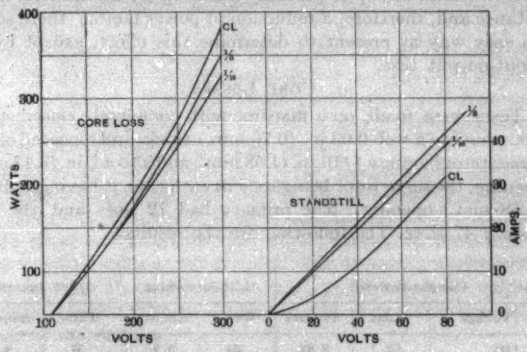
The full-load current is 25 amperes so that there will be considerable saturation and tufting of flux at load current, and, therefore, increased core loss. The following standstill voltages and currents show the effect of saturation.

Volts	Closed slots Amperes	1/16-in. opening Amperes	1/8-in. opening Amperes
20	4	9.5	10.5
30	6½	14.5	15.8
40	11.6	19.5	21.0
60	22	29.5	31.2
80	32	39	41.5

The curves herewith show more clearly the saturation effect of the completely closed slots.

A method of testing induction motors largely used in Europe measures the input by wattmeters; the core loss, friction, and

primary I^2R are subtracted from the input, and the result is called the primary output. This is multiplied by the per cent of synchronous speed (1 per cent slip) and called the secondary output. While not strictly correct it is as close as is commercially practicable, except in cases of bar-wound stators or non-proportional impedance curves.



The losses method does not show correct results when the standstill ampere curve is bent as shown above.

Results of Tests: Load Tests

A number of tests on wire-wound machines with partly open and straight slots have been made, checking efficiency and power factor by input-output method with the method of losses (A. I. E. E. method.) These cover machines from fractional to 150 h.p. From 29 tests ten showed lowest efficiency by loss method, and the remaining 19 showed lowest by brake test. The average is about three-fourths of one per cent lower by brake than by losses.

Two bar-wound stator machines showed 1.4 per cent and 3 per cent, respectively, lower by load test than by losses method. Unfortunately, tests were not made on the stator alone to determine eddy losses. As these were tested commercially no great accuracy should be expected, but they show a general agreement of the two methods.

The following are the results from a certain induction motor which has completely closed slots in both stator and rotor: the

efficiency from method of losses was 0.881, while from an input-output test 0.774 was obtained; the power factor by losses method was 0.901, and from input-output tests 0.903.

This result is rather startling, but the tests have been made carefully, and while not conclusive, show that the question of load losses on completely closed slot motors may become serious. As both stator and rotor are wire-wound with small wire, and the I^2R total checks very closely with the watts at standstill, it would seem the extra losses are due to saturation of the

Horse power	Rev. per min.	Efficiency by losses method	Efficiency by brake method	Difference per cent
10	1800	85.85	84.2	1.65
7½	1500	81.2	79.7	1.5
5	900	85.7	85.2	0.5
3	1200	80.4	80.5	—0.1
2	1000	80.2	79.3	0.9
1	1200	80.9	82.6	—1.5
1.5	1000	75.5	74.85	0.65
¾	1200	70.1	72.2	—2.1
1	800	56.2	53.5	2.7
1/5	900	36.2	34.8	1.4
¾	1200	68	70.3	—2.3
1	450	51.6	50.2	1.4
½	600	46.3	43.8	2.5
5	1800	85.9	84.6	1.3
7½	1800	85.5	87.4	—1.9
2	1800	82.6	84.2	—1.6
10	1800	89.8	90.3	—0.5
9	1200	84.8	86.5	—1.7
2	1800	86.6	86.3	0.3
20	1800	87.2	89.4	—2.2
1	1800	81.2	78	3.2
7½	1800	87	86.9	0.1
150	600	93.2	91.8	1.4 bar-wound
36	360	88.1	85.1	3 " "
50	600	89.4	89	0.4
20	800	88.2	88.6	0.4
30	800	90.5	91	—0.5
10	1200	87.5	86	1.5
10	1200	85.6	87	1.4

teeth. The core loss running light is 6 per cent of the rated output.

A further test has been made on a motor with partly closed primary slots and completely closed rotor slots, the thickness of the web being one mm.: the core loss running light was 2.3 per cent (approximately ⅓ of what would be obtained if one member were of the usual straight slot construction).

At one-half load the difference in efficiency between the loss method and input-output was 1.7 per cent, at three-quarter load 2.2 per cent, at full load 2.8 per cent, at one-half load 3.4 per

cent. The corresponding differences in power factor were 1 per cent, ½ per cent, 0.2 per cent, and 0.2 per cent.

The load test was taken by a friction brake and is the average of a number of readings, it being necessary to take a number on account of scattering points.

The motor was designed to have a large core loss and small copper loss, therefore, the load losses, due to saturation of the thin overhang, are not as large as would be the case in a motor of more ampere-turns per slot, such as a standard type.

The results, however, show a decided load loss, increasing approximately proportionally to the load.

The results of these two load tests are in agreement, and seem to indicate that load losses of considerable magnitude may be expected when the iron paths are saturated, due to load current.

In connection with the above, to show the effect of tufted flux, certain tests were made on machines with and without magnetic wedges; the magnetic wedge approaches the condition of a nearly closed slot. Where the wedge was properly made and insulated the core loss was one-half to one-third of the corresponding straight slot; with a poorly insulated wedge, however, the losses increased from two to three times, showing that magnetic wedges require very careful design and handling. Due to the structure of the wedges more or less of an air path was included by the wedges and the short-circuited current was directly proportional to the voltage.

The effect of filing and turning on the cores is shown as an excess core loss during the excitation or running light test; it is constant for a given machine, but is largely the cause of the different core loss measurements on duplicate machines.

Designing engineers are aware of the above conditions and the general practise at present is to build motors with an air path somewhere in the magnetic circuit of each slot.

Present experience seems to indicate that where there is no saturation or bend in the standstill or impedance curve, there are no appreciable load losses; where wire winding is used no allowances are necessary for copper losses; where bar-wound machines are used it is necessary to test the stator without the rotor to determine the stator copper losses; bar-wound rotors show a greater loss and a lower inductance at standstill than when running. Half or quarter frequency tests will largely determine the eddy losses which modify secondary slip and reactance. The slip is a direct measure of the secondary loss.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

STRAY LOSSES IN INDUCTION MOTORS

BY A. M. DUDLEY

Section 167 of the Standardization Rules, referring to induction motors, states, "These losses (load losses) may for practical purposes be determined by measuring the total power, with the rotor short-circuited at standstill and a current in the primary circuit equal to the primary energy current at full load. The loss in the motor under these conditions may be assumed to be equal to the load losses plus I^2R losses in both primary and secondary coils."

It is the purpose of this paper to point out that the losses as measured according to this section in many cases include losses which are not present when the motor is operating at normal full-load speed and which cannot, therefore, justly be called load losses and charged against the efficiency of the motor as calculated by the "summation of losses" method.

It is the further purpose to point out a method by which the separate losses in a motor, including the load losses, may be segregated from no-load readings with reasonable assurance that the motor efficiency as figured therefrom will be as close to the efficiency measured by the input-output readings when the motor is running under load as is the limit of error necessarily encountered in taking these readings, even with laboratory methods.

The reason for presenting the problem as it is stated in the last paragraph appears from a consideration of the practical difficulties encountered in testing units of such a size as to make it difficult to secure facilities for running an actual load test, either on the premises of the manufacturer or after installation, in regular service.

The limitations of the manufacturer in this case are usually

(a) lack of mechanical apparatus for connecting the motor to a suitable load, (b) lack of a suitable load, either mechanical or in the nature of an electrical generator, and (c) insufficient power to operate the unit when developing full load.

The limitations of the ultimate user which act against a successful test after installation are (a) inability to control the load within reasonable variations while observations are being taken; (b) lack of proper facilities in the way of precision instruments and other appliances for suitably conducting such tests, and (c) lack of a sufficient number of properly trained observers for taking the readings.

Added to the foregoing disadvantages is the further one, pointed out in Mr. Olin's paper in the 1912 TRANSACTIONS*, that errors in observations on load tests, or so-called input-output tests, reduce their reliability below that obtained by making a careful determination of the separate losses from no-load readings and determining the efficiency by the "summation of losses" method.

Recognizing these facts, it has become standard practise on induction motors of small and moderate capacities to compute efficiencies in the following manner: A reading is taken of the amperes and watts input to the motor at full voltage when running idle. From this is subtracted the I^2R losses due to the no-load current and the remainder is considered to be the friction and windage plus the "rotation loss" or so-called "core loss." There is a slight error in the last item due to the fact that the "core loss" should be taken at the induced rather than at the applied voltage, but in all but very small units this error is small. To the foregoing losses are added the primary copper loss at proper full-load current and temperature, and the secondary copper loss as shown by full-load "slip" from synchronous speed, measured by brake. These total losses are added to the output at the current chosen, and the result considered the input, and the efficiency computed therefrom.

So soon, however, as the unit becomes of a size where it is difficult or impossible to take the slip under actual load, a question immediately arises as to the amount of the secondary copper loss. When recourse is had to Section 167 of the Standardization Rules quoted above, it offers no means of segregating the load losses from the secondary copper loss after the primary copper loss has been subtracted from the watts input to the motor at standstill at normal voltage.

*TRANS. A.I.E.E., 1912, XXXI, Part II, p. 1695.

It is this uncertainty that makes necessary an analysis of the nature of these so-called load losses and the outlining, if possible, in the Standardization Rules of the Institute, of a method for segregating this loss from the other losses in the machine.

A consideration of the possible causes of such losses suggests two sources:

a. A distortion of the main field form due to armature reaction caused by working load currents, or

b. Eddy currents in the copper conductors due to the main field.

On account of the symmetry of the core and distribution of the windings it may safely be assumed that there is very little, if any, distortion of the field form, due to cause "a," and any loss so set up may be neglected.

There remain the eddy currents in the copper due to the main field.

It is here to be noted that with the rotor at standstill and a current of normal frequency flowing in the primary, the frequency of the secondary current is the same as that of the primary. At normal full-load speed, however, the frequency of the rotor is very low, being only the same percentage of the primary frequency that the slip is in percentage of synchronous speed. From this it follows at once that where the cross-section of the rotor conductors is such as to permit setting up of eddy currents there may be a very appreciable proportion of the watts at standstill due to eddy currents in the rotor copper which are not present when the rotor is running up to speed.

Added to this item is one of less consequence, due to iron loss in the secondary at standstill which is not present at full speed.

It is, therefore, proper to charge against the motor the eddy current losses in the primary copper but exclude those due to eddy currents in the secondary copper. To get at a method of approximating these losses more closely, a series of readings was taken on a motor with currents of varying frequency in the primary windings. These results are shown in Fig. 1. From these readings it appears that as the frequency approaches zero the watts input becomes very nearly that due to the copper losses in primary and secondary caused by usual resistances of the windings alone. There still remains the question of segregating the increased loss at normal frequency into eddy current loss in the primary and secondary so that the machine need not be

charged with a loss occurring in the secondary at standstill which is not present at full speed.

There are, no doubt, several ways in which this could be accomplished, of which two may be mentioned here.

1. The increased losses over the ordinary I^2R losses as shown in Fig. 1 may be divided into primary eddy current loss and secondary eddy current loss, in proportion to the square of the depth of the conductor in the slot in each member. This is, in a way, somewhat empirical, but it would probably give as close results as can be arrived at by other methods, and it has the

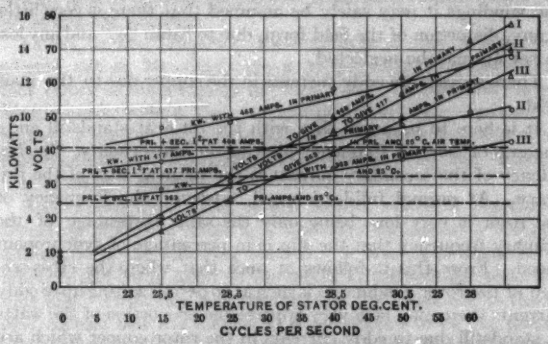


FIG. 1—VARIATION OF EDDY CURRENT LOSSES IN PRIMARY AND SECONDARY COPPER WITH VARIATION IN FREQUENCY

Induction motor, 450 h.p., three-phase, 60 cycles, 440 volts. 8 poles, 870 rev. per min.
Rotor resistance at 25 deg. cent. 0.314$^{\omega}$ terminal to terminal.
Stator resistance at 25 deg. cent., 0.128$^{\omega}$ terminal to terminal
Readings taken with secondary short-circuited and locked. Amperes in primary are read per phase.

advantage of being simple, since the details of design are usually readily available when conducting tests.

2. The rotor, if of the phase-wound type, could be removed from the stator and sufficient voltage applied to its terminals to cause full-load current to flow in the windings. A measurement of the watts input under this condition as compared with the straight I^2R due to the resistance of the windings would indicate the amount of the eddy current loss in the secondary copper and this should be deducted from the total watts input to the machine at standstill. The remainder should be charged against the machine as the usual I^2R loss in the primary and secondary

plus the proper load loss due to eddy currents in the primary conductors caused by the main field.

At this point it might be brought out that the value of the secondary current at full load may be taken from the Heyland diagram or some modification thereof, or it may, for all practical purposes, be taken from the following formula: Secondary current per terminal at full load = horse power output in watts + secondary I^2R loss + bearing friction and windage ÷ K × volts between collector rings at standstill with normal voltage applied to the primary. $K = 1.73$ for three-phase rotor and $= 2$ for two-phase rotor.

In the case of a squirrel-cage motor the rotor could be removed from the stator and sufficient voltage applied to the terminals of the stator to cause full-load current to flow therein. A measurement of the watts input under this condition as compared with the straight I^2R loss would indicate the amount of eddy current loss in the primary copper. This amount, added to the ordinary primary and secondary copper loss determined by the method shown in Fig. 1, would indicate the proper copper loss to be charged against the machine.

The foregoing discussion has reference to units of fairly large capacity. A careful study of smaller machines, where the size of the primary conductors does not exceed a No. 10 round wire, shows that there are practically no load losses. It is not necessary to burden this paper with a long tabulated statement of the data investigated to prove this point, but a brief statement will cover the results of this investigation.

Sixty-nine motors were selected, entirely at random. They were of both the wound rotor and squirrel-cage types, open and closed slots, 60 and 25 cycles, two- and three-phase, voltages from 220 to 2200 and capacities from 3½ h.p. to 150 h.p. A comparison was made of the full-load efficiencies as determined by careful prony brake tests, with the efficiencies by summation of losses. In the efficiencies by losses, no item was entered for load losses. The only losses considered were primary and secondary I^2R losses, the rotational or core losses and the mechanical losses due to bearing friction and windage. It was assumed that if there were any load losses, the efficiency by brake test would be consistently lower than by losses. Such was not found to be the case. Out of 69 machines the efficiency by brake test was higher in 34 cases; the efficiency by losses was higher in 32 cases and the two were the same in three cases. From these data,

and an experience over a period of several years covering a large number of machines, the conclusion is drawn that for machines in which the primary conductor does not exceed in size a No. 10 wire, B. & S. gage, it may be assumed that there is no load loss or that it is negligible in amount.

Based upon the foregoing argument, the recommendation is made that Section 167 be modified to cover two conditions:

1. That it be recognized that machines having primary conductors of small cross-section have no appreciable load loss, and that a summation of loss method based upon the usual I^2R losses measured by resistance and slip is sufficiently accurate for determining their efficiency.

2. That on machines having primary conductors of comparatively large cross-section and consequently some load loss in the primary copper, a method be approved for determining the efficiencies from no-load readings, substantially as described in this paper.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

NOTES ON INDUCTION MOTOR LOSSES

BY R. W. DAVIS

The object of this paper is not a comprehensive treatment of the subject, but a few notes on the data obtained from numerous tests on induction motors. It is hoped that this and the other papers on the same subject will lead to further discussion and be of assistance in bringing about a revision of the Standardization Rules for the determination of fixed and stray losses in induction motors.

A large number of tests on motors of various sizes for 25- and 60-cycle circuits were compared and the data tabulated. The data obtained check the losses as given by the Standardization Rules, with the exception of the fixed and stray losses.

The power input to the motor when running at rated voltage and without load is taken by the Institute rules as the fixed loss: *i.e.*, friction, windage, core and copper losses which may exist in multiple circuit windings. This gives too large a figure, since it includes the stator copper loss due to the magnetizing current. This copper loss is quite appreciable in low-speed motors. The true fixed loss should therefore be taken as the power input minus the stator copper loss produced by the magnetizing current.

The stray losses may be grouped under two general divisions: the losses in the stator, and those in the rotor. The writer is not aware of any satisfactory method of determining the stray losses in the stators of induction motors. An induction motor stator is very similar in construction to the stator of a definite pole alternator of corresponding rating, and tests on the latter apparently show that with properly built cores the stray loss in the magnetic circuits of definite pole alternators is negligible. The

total measured loss checks very closely with the sum of the I^2r loss and the computed eddy current loss in the conductor.

Oscillograms showing the distribution of the flux in induction motor stators indicate that there is very little change in its distribution from no-load to full. It therefore seems to the writer that the stray losses in the magnetic materials of induction motor stators should be neglected. The data on stray loss in copper, given in the table, were computed by the same method which was found satisfactory for definite pole synchronous machines. These stray losses are expressed in per cent of the normal stator copper loss.

Horse power	Rev. per min. syn.	Volts	Cycles	Per cent stator stray loss	Full load slip		Locked losses		
					Test	Calc.	Stator	Rotor	Total stray
30	500	2200	25	*	3	2.4	41.2	23.5	35.3
40	750	440	25	5	4.2	3.5	44.3	38.2	17.5
75	720	440	60	1	3.3	3.5	48.1	33	18.9
100	500	2200	25	*	2.4	2.4	45	45	10
100	600	440	60	*	3.1	2.8	41.5	47.3	11.2
100	720	220	60	16	3.3	3.5	35.3	47	17.7
200	500	440	25	3	2.8	2.8	34.4	50	15.6
200	600	440	60	1	2.3	2.4	38	50	12
250	600	440	60	*	2.7	2.6	30.2	40.8	29
300	450	550	60	6	1.6	1.4	32.7	23.8	43.5
300	600	550	60	9	1.7	1.6	37.7	44.3	18
350	600	550	60	9	1.9	2	36	43.5	20.5
400	600	440	60	5	1.6	1.7	30.8	38.4	30.8
500	514	440	60	1	0.9	0.8	31	38	31
600	300	550	60	9	1.6	1.4	29	30.8	40.2
600	600	2200	60	2	1.3	1.2	29.2	35	35.8
800	750	6600	25	*	1.3	1.4	33	33	34
600	1200	2200	60	2	0.9	0.9	33.4	40.5	26.1

*Less than ½ per cent.

The stray losses in the rotor of an induction motor are a function of the rotor frequency and therefore proportional to speed. At standstill, full frequency is induced in the rotor, very greatly increasing the rotor iron loss and the eddy current loss in the conductor. The writer has taken advantage of this in designing squirrel-cage motors, obtaining good starting characteristics and low slip at full load with a resultant efficiency comparable with that of a wound-rotor motor. The present Institute rule for measuring stray losses includes these high losses at standstill as a part of the total loss in the motor at full load. The tests show that the slip at full load corresponds to the I^2r loss by resist-

ance measurement and that the stray loss in the rotor at standstill is not present at full load in machines of small slip. The calculated slip given in the table is based upon the assumption that the only loss in the rotor is the copper I^2r loss determined from the resistance measurement. The test slip measured at full load is the average of a number of readings, and checks the calculated slip within the limit of experimental error. The copper and stray losses in the table are taken from the lock test and expressed in per cent of the total loss on short-circuit. The tests are on wound-rotor motors, with the exception of the last, which is on a squirrel-cage machine with the bars bolted and soldered to the end rings, removing all poor contacts between bars and end rings.

Many of the tests checked were incomplete in some respect. Only those tests which were complete have been included in the table, although the data of all tests, in so far as they were considered reliable, were used in arriving at conclusions. Neglecting any small stray loss which may exist in the magnetic materials of the stator, the stator stray loss is proportional to the stator copper loss, the percentage loss depending upon the degree of lamination of the conductor and the frequency. The average stray loss in both 25- and 60-cycle machines is about six per cent of the stator copper loss. In rotors of small slip there is no stray loss shown within the limits of experimental error, and in rotors of large slip the stray loss under full-load test is only a fraction of the rotor stray loss at standstill. The total rotor loss under full load is in every case less than the combined copper and stray losses obtained from the short-circuit test.

It therefore seems desirable that an average value of stator stray loss in per cent of stator copper loss be adopted as a standard. In squirrel-cage motors and small wound-rotor motors, where the slip is usually greater than two per cent, the total rotor loss should be determined from the slip reading when operating at full load. The rotor loss should be taken as the copper I^2r loss from resistance measurements, in large wound-rotor motors where the slip is less than two per cent and a full-load slip reading is not readily obtained.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

LOSSES IN TRANSFORMERS

BY W. W. LEWIS

The losses in transformers, as defined in the Standardization Rules of the American Institute of Electrical Engineers, Sections 157-159, are as follows:

157 MOLECULAR MAGNETIC FRICTION AND EDDY CURRENTS measured at open secondary circuit, rated frequency, and at rated voltage $-I\,r$, where I = rated current, r = resistance of primary circuit.

158 RESISTANCE LOSSES, the sum of the $I^2\,r$ losses in the primary and in the secondary windings of a transformer, or in the two sections of the coil in a compensator or auto-transformer, where I = rated current in the coil or section of coil, and r = resistance.

159 LOAD LOSSES, *i.e.*, eddy currents in the iron and especially in the copper conductors, caused by the current at rated load. For practical purposes they may be determined by short-circuiting the secondary of the transformer and impressing upon the primary a voltage sufficient to send rated load current through the transformer. The loss in the transformer under these conditions, measured by wattmeter, gives the load losses $+\,I^2\,r$ losses in both primary and secondary coils.

Transformer losses more naturally group themselves into two divisions: *no-load losses and load losses.*

The no-load losses are the losses that exist when potential is impressed on the primary of the transformer, with open secondary circuit, and include the loss in the iron and the loss in the insulation; or, *core and dielectric losses.*

The load losses are the losses caused by the load current, and include the loss due to the resistance of the copper and the loss due to the stray or leakage field; or, *resistance* and *stray losses.*

It is the purpose of this paper to give an idea of the magnitude of the stray and dielectric losses, and to recommend certain amendments to the above sections of the Standardization Rules. The term "load loss" will be used in the broad sense (including resistance and stray loss), and the term "stray loss" will be used when referring to the loss defined in Section 159.

TABLE I

STRAY LOSS

Frequency cycles	Rating kv-a.	Rated voltage High-tension	Rated voltage Low-tension	Impedance volts in per cent	I^2R watts	Impedance watts	Stray loss watts	Stray loss in per cent of I^2r	Stray loss in per cent of rated kv-a.
			CORE TYPE TRANSFORMERS						
25	100	6,600	2,200	1.76	950	1041	91	9.58	0.091
"	"	11,000	460	1.81	1105	1140	35	3.16	0.035
"	"	15,000	375	1.89	1165	1190	25	2.14	0.025
* "	"	33,000	390	15.0	1565	1710	145	9.27	0.145
* "	"	22,000	740	15.7	1440	1496	56	3.89	0.056
* "	"	13,200	370	17	1475	1794	319	21.60	0.319
* 25	145	11,000	370	14.92	1828	2284	456	25	0.314
25	150	12,600	460	2.25	1865	1890	25	1.34	0.017
"	"	6,600	440	2.27	2137	2150	13	0.61	0.009
"	"	20,000	460	2.30	1490	1605	115	7.71	0.077
* 25	165	6,600	430	17	1711	2560	839	49.5	0.508
* "	"	6,600	430	17.5	1915	2445	530	27.7	0.322
* 25	185	23,500	480	15.6	2300	2910	610	26.5	0.330
25	200	22,000	440	2.13	2050	2160	110	5.37	0.055
"	"	11,000	2,200	2.25	1880	1960	80	4.25	0.040
"	"	6,600	2,300	2.44	1980	2100	120	6.06	0.060
25	250	11,000	2,300	1.46	2140	2180	40	1.87	0.016
"	"	13,200	480	2.39	2805	2870	65	2.32	0.026
25	300	11,000	2,300	2.19	2565	2663	98	3.82	0.033
25	350	12,000	2,400	7.81	2730	2950	220	8.06	0.063
"	"	11,000	430	11.7	2575	3560	985	38.2	0.282
25	400	11,000	2,200	2.63	2460	2655	195	7.94	0.049
60	100	12,480	2,300	1.92	1093	1107	14	1.28	0.014
"	"	6,600	460	2.58	1005	1060	55	5.46	0.055
"	"	10,500	2,300	2.59	797	822	25	3.14	0.025
"	"	6,600	2,400	4.23	800	1020	220	27.5	0.220
* "	"	11,000	370	15.1	832	1140	308	37.0	0.308
* "	"	13,200	370	15.3	945	1265	325	33.9	0.325
* "	"	15,000	370	16.9	893	1158	265	29.7	0.265
60	150	6,600	2,300	2.6	1100	1140	40	3.64	0.027
"	"	5,720	2,300	2.83	1214	1318	104	8.57	0.069
"	"	6,600	240	3.8	932	1400	468	50.2	0.312
* 60	165	13,200	430	16.1	1174	1880	706	60.1	0.428
60	200	6,600	2,200	1.9	1020	1160	140	13.72	0.070
"	"	6,600	2,400	1.92	1060	1118	58	5.47	0.029
"	"	9,350	2,080	2.18	1577	1705	128	8.13	0.064

TABLE I—*Continued.*

Frequency cycles	Rating kv-a.	Rated voltage: High-tension	Rated voltage: Low-tension	Impedance volts in per cent	I^2R watts	Impedance watts	Stray loss watts	Stray loss in per cent of I^2r	Stray loss in per cent of rated kv-a.
60	250	6,600	550	2.25	1435	1700	265	18.48	0.106
"	"	6,600	480	2.50	1338	1585	247	18.48	0.099
"	"	6,300	200	3.75	2210	2803	593	26.8	0.237
60	300	6,940	2,300	1.72	1836	1925	89	4.85	0.030
"	"	6,600	2,300	2.27	1626	1920	294	18.1	0.098
"	"	22,000	370	4.18	1790	2400	610	34.1	0.203
"	"	6,000	240	4.19	2150	2810	660	30.5	0.220
60	350	11,000	2,300	1.67	1792	1880	88	4.91	0.025
"	"	6,600	2,300	2.4	1665	2050	385	23.1	0.110
60	350	10,000	440	3.22	1865	2200	335	18.0	0.096
"	"	34,650	430	18.2	1885	3000	1115	59.2	0.319
60	400	6,800	2,200	2.19	2537	2740	203	8.02	0.051
"	"	22,000	2,500	2.89	2040	2265	225	11.02	0.056
"	"	6,300	200	3.35	2380	3040	660	27.7	0.165
60	500	10,000	3,450	2.03	1905	2330	425	22.3	0.085
"	"	6,600	2,300	2.20	2080	2700	620	29.8	0.124
"	"	10,000	2,300	3.14	3216	3471	255	7.94	0.051
				SHELL TYPE TRANSFORMERS					
40	200	10,000	90	3.76	2350	2740	390	16.6	0.195
25	250	6,600	110	1.64	2310	2400	90	3.9	0.036
25	275	6,940	199	2.96	2905	3280	375	12.9	0.136
60	300	34,600	2,300	3.02	2270	2415	145	6.4	0.048
60	375	6,600	240	4.30	2600	2965	365	14.0	0.098
60	400	44,000	2,300	3.53	2250	2525	275	12.2	0.069
60	500	2,200	608	3.75	3240	4060	820	25.3	0.164
"	"	38,100	7,500	2.90	2960	3115	155	5.25	0.031
"	"	14,450	2,500	3.26	2570	3265	695	27	0.139
"	"	14,450	2,500	3.29	2565	3145	580	22.6	0.116
"	"	13,200	2,550	3.83	2240	2860	620	27.7	0.124
"	"	15,000	2,300	2.15	2800	3060	260	9.3	0.052
"	"	13,200	2,530	1.58	2090	2270	180	8.63	0.036
"	"	6,600	2,300	2.45	2860	3095	235	8.22	0.047
"	"	11,000	2,300	3.01	2525	3260	735	29.1	0.147
"	"	14,000	2,440	3.34	3055	3340	285	9.35	0.057
60	500	23,000	6,600	2.83	3570	4040	470	13.2	0.094
"	"	25,087	2,500	4.68	3420	3890	470	13.7	0.094
60	600	6,930	3,300	2.48	3740	3780	40	1.07	0.007
"	"	33,000	13,860	3.36	2800	3380	580	20.7	0.097

TABLE I—*Continued.*

Frequency cycles	Rating kv-a.	Rated voltage		Impedance volts in per cent	I^2R watts	Impedance watts	Stray loss watts	Stray loss in per cent of I^2R	Stray loss in per cent of rated kv-a.
		High-tension	Low-tension						
40	750	22,000	600	3.85	4900	5850	950	19.4	0.127
60	750	10,000	3,450	3.18	3965	4760	795	19.9	0.106
*	*	4,000	2,300	3.23	3380	4640	1260	37.4	0.168
*	*	6,600	2,300	4.14	4250	5570	1320	31.1	0.176
*	*	35,475	2,035	4.23	3100	3855	755	24.3	0.101
*	*	60,000	480	4.88	4325	5025	700	16.2	0.093
60	900	23,000	2,300	3.51	5140	6170	1030	20.0	0.113
25	1000	60,000	11,000	4.15	8460	9040	580	6.85	0.058
60	1000	22,000	2,300	2.13	5500	5980	480	8.74	0.048
*	*	21,000	2,500	2.90	5785	6565	780	13.5	0.078
*	*	110,000	22,000	5.00	7070	7300	230	3.25	0.023
*	*	110,000	22,000	5.00	7165	7330	165	2.58	0.017
60	1500	33,000	2,300	4.41	6570	8200	1630	24.8	0.109

* Transformers equipped with internal magnetic shunts.

NOTE.—Each item above represents an average of from one to six transformers.

I. STRAY LOSS

Magnitude of Stray Loss. Table I shows the value of the stray loss, in a number of commercial transformers selected at random. It will be seen that there is apparently no definite relation between impedance voltage and stray loss, or rated voltage and stray loss, although in general the loss increases with increase in impedance voltage, and also for a given size transformer, increases as the low-tension voltage decreases.

Table II gives the results of some impedance tests on an experimental core type transformer, rated 60 cycles, 165 kv-a., 11,000 volts high-tension and 430 volts low-tension. This transformer has four high-tension coils of 308 turns each (two coils per leg) and two low-tension coils of 24 turns each (one coil per leg). The high-tension conductor is 0.215 by 0.055 in. (5.46 by 1.4 mm.) copper, edge-wound; the low-tension conductor consists of ten strips of 0.5 by 0.095 in. (12.7 by 2.4 mm.) copper, arranged five wide and two high.

The first set of readings was taken under normal conditions at 60 cycles. Then some bundles of laminated steel (20 bundles per leg, each containing 18 sheets) were placed horizontally be-

tween high-tension and low-tension coils, to form a magnetic shunt, and the remaining three sets of readings were taken at 25, 40 and 60 cycles. The introduction of the shunt has the tendency to exaggerate the losses and therefore to give better readings. The results are plotted in the curves of Fig. 1.

This transformer requires 4 per cent of the normal voltage

TABLE II

IMPEDANCE TESTS—VARIATION WITH CURRENT AND FREQUENCY. TRANSFORMER 60 CYCLES, 165 KV-A., 11,000 VOLTS TO 430 VOLTS

Low-tension (inner) winding short-circuited. (See Fig. 1.)

Frequency cycles	Impedance volts	Per cent normal volts	Amperes	Per cent normal amperes	Impedance watts	I^2R watts	Stray loss in per cent I^2R	Remarks
60	209	1.9	7.51	50.1	317	294	7.83	
"	312	2.84	11.20	74.6	705	662.5	6.42	
"	423	3.85	14.9	99.4	1270	1177	7.8	
"	529	4.81	18.8	125.2	2050	1839	11.48	
"	633	5.75	22.5	150	2915	2648	10.08	
25	254	2.31	3.75	25	82	73.5	11.55	With magnetic shunts
"	526	4.79	7.55	50.4	387	294	31.6	
"	730	6.64	11.25	75	839	662.5	11.54	
"	876	7.97	15.1	100.8	1500	1177	28.3	
"	985	8.95	18.85	125.8	2190	1839	19.1	
"	1076	9.78	22.6	150.8	3040	2648	14.8	
40	427	3.88	3.75	25	109	73.5	48.3	With magnetic shunts
"	835	7.6	7.55	50.4	459	294	56.1	
"	1167	10.6	11.25	75	945	662.5	42.7	
"	1393	12.68	15.1	100.8	1680	1177	42.8	
"	1570	14.28	18.85	125.8	2505	1839	36.3	
"	1713	15.6	22.6	150.8	3405	2648	28.6	
60	580	5.28	3.75	25	—	73.5	—	With magnetic shunts
"	1256	11.4	7.55	50.4	561	294	90.8	
"	1750	15.9	11.25	75	1143	662.5	72.5	
"	2090	19.0	15.1	100.8	1880	1177	59.8	
"	2330	21.2	18.85	125.8	2650	1839	44.1	
"	2570	23.38	22.6	150.8	3725	2648	40.6	

at 60 cycles to force full-load current through the windings, and its impedance losses are 8 per cent in excess of the calculated $I^2 r$ loss. Equipped with magnetic shunt, the transformer requires 19 per cent of the normal voltage at 60 cycles to force full-load current through the windings. Its impedance losses are 60 per cent in excess of the calculated $I^2 r$ loss.

In this test, the high-tension (outer coils) were excited and the low-tension (inner coils) short-circuited. Considerable difference results if the low-tension is excited and the high-tension short-circuited. See Table III. This is due to the dif-

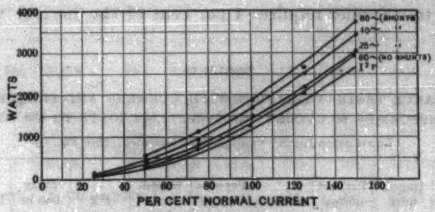


FIG. 1—IMPEDANCE TESTS, 165-KV-A. TRANSFORMER
See Table II.

ferent distribution of the flux in the two cases, and the stray loss is reduced to 50 per cent of the $I^2 r$ loss.

Tests were made on an experimental transformer rated 60 cycles, 8 kv-a., 800 volts primary and 800 volts secondary. Each winding was composed of two coils, one on each leg, of

TABLE III

IMPEDANCE TEST.—TRANSFORMER 60 CYCLES, 165 KV-A., 11,000 VOLTS TO 430 VOLTS

High-tension (outer) winding short-circuited

Frequency cycles	Impedance volts	Per cent normal volts	Amperes	Per cent normal amperes	Impedance watts	I^2R watts	Stray loss in per cent of I^2R	Remarks
60	47.8	11.12	192	50	490	294	66.6	With magnetic shunt
"	66.0	15.35	289	75.3	1080	662.5	63	
"	79.5	18.5	386	100.5	1770	1177	50.4	
"	86.0	20.0	443	115.2	2250	1560	44.3	
"	89.5	20.8	474	123.5	2460	1839	33.8	

160 turns of 0.05 by 0.2 in. (1.27 by 5.08 mm.) copper conductor. The outside coils were excited and the inner coils short-circuited. The tests recorded in Table IV and plotted in Fig. 2 were made, first, with no core; second, with bundles of steel placed vertically between the primary and secondary (two

bundles of 12 sheets each per leg); third, with the laminated steel core in place and no shunts; fourth, with steel core, and magnetic shunts in place between primary and secondary. From these readings, we can separate in a measure the loss in the copper and the core, but only approximately, as the flux distribution is not the same in any two cases.

When a transformer is loaded by the impedance method, the secondary ampere-turns are not equal and opposite to the primary ampere-turns, which is the condition necessary to

TABLE IV

IMPEDANCE TESTS—VARIATION WITH FREQUENCY—TRANSFORMER 60 CYCLES, 8 KV-A., 800 VOLTS PRIMARY, 800 VOLTS SECONDARY

Inside coils short-circuited. (See Fig. 2)

Frequency cycles	Impedance volts	Per cent normal volts	Amperes primary	Amperes secondary	Impedance watts	I^2R watts	Stray loss in per cent of I^2R	Remarks
30	11.25	1.41	10	7.2	79	78.8	0.25	Air core
40	13.10	1.64	10	7.8	83	82.4	0.73	
50	15.10	1.89	10	8.25	87	85.2	2.11	
60	16.90	2.11	10	8.47	90	86.7	3.81	
30	50	6.25	10	3.63	72.2	63.6	13.5	Air core
40	67	8.37	10	3.96	79	64.6	22.3	magnetic
50	84	10.5	10	4.18	85.1	65.3	30.3	shunts
60	98.5	12.3	10	4.27	91.2	65.6	39.0	
30	12.95	1.62	10	9.92	98.5	97.1	1.44	Iron core
40	13.90	1.74	10	9.92	99.5	97.1	2.47	
50	15.90	1.99	10	9.92	100.8	97.1	3.81	
60	17.80	2.22	10	9.92	102.2	97.1	5.25	
30	64	8.0	10	9.85	109.4	96.6	13.25	Iron core
40	86	10.75	10	9.85	114.3	96.6	18.5	magnetic
50	107	13.4	10	9.85	121.3	96.6	25.6	shunts
60	129	16.1	10	9.85	127.5	96.6	32.0	

have no leakage flux. (See third test, Table IV.) This introduces an error in the loss, which, however, is very slight for transformers of ordinary reactance.

Relation between Impedance Watts and Load Losses. To show the relation between the impedance watts and the actual load losses, that is, losses caused by rated current under operating conditions, a series of tests is recorded. The 60-cycle, 165-kv-a., 11,000 volts high-tension and 430 volts low-tension transformer, previously described, with the steel magnetic

shunt in place between high-tension and low-tension windings, was used. A so-called "bucking" heat run was made, *i.e.*, with the 165-kv-a. transformer and a 365-kv-a. transformer of the same voltage rating, the high-tension windings being connected in series, bucking, and supplied with sufficient voltage to force full-load current through the winding of the 165-kv-a. transformer, and the low-tension windings being connected in multiple and excited at normal volts. This is the regular manner of performing heat runs on transformers, and its effect is to supply core loss and impedance watts to the transformer. Another run was made with the experimental transformer loaded on a water box, with normal voltage supplied to the high-tension and normal amperes delivered on the low-tension. The results are given in Table V, together with a set of check readings.

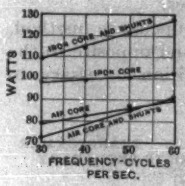


FIG. 2—IMPEDANCE TEST, 8-KV-A. TRANSFORMER

See Table IV.

TABLE V

HEAT RUNS

TRANSFORMER 60 CYCLES, 165 KV-A., 11,000 VOLTS TO 430

Self-cooled

Frequency cycles	Kind of load	Exciting volts	Load amperes	Room temperature	Rise oil	Rise top of tank	Rise bottom of tank	Rise primary	Rise secondary
60	Bucking	430	15	21	39	36	17	37	44
60	Dead	11,000	388	21	36	33	17	36	—
Check run:									
60	Bucking	430	15	20	36	32	28	37.5	44.5
60	Dead	11,000	384	22	36	33	29	38.5	45

Normal amperes: high-tension 15, low-tension, 384.

All rises in deg. cent. above room temperature.

In the first run the thermometer at bottom of tank was placed nearer to bottom than in second run.

The experimental transformer was then placed in a tank containing cooling coils and operated as a water-cooled transformer on both bucking and dead (water box) load. Three runs were made: first, with 125 per cent normal amperes and 1.3 gal. of water per min.; second, with 125 per cent normal amperes and 0.66 gal. of water per min.; third, with 150 per cent normal

amperes and 0.5 gal. water per min. The results are given in Table VI.

We may conclude from the results of Tables V and VI that the bucking method of heat run (supplying core loss and impedance watts) gives substantially the same losses as supplied under normal load conditions (as approximated by the water-box run).

To further check this point, tests are recorded of a small transformer rated 60 cycles, 110 volts primary, 50 amperes secondary. This was built on a two-legged core, with one coil on each leg. The coils consisted of 115 turns of 0.24 by 0.12 in. (6.1 by 3.05 mm.) copper, and 48 turns of 0.048 by 0.13 in.

TABLE VI
HEAT RUNS
TRANSFORMER 60 CYCLES, 165 KV-A., 11,000 VOLTS TO 430 VOLTS
Water-cooled

Frequency cycles	Kind of load	Exciting volts	Load amperes	Gal. water per min.	Room temperature	Temperature ingoing water	Rise water	Rise oil	Rise tank
60	Bucking	430	18.8	1.3	23	9.3	11.5	21	17
60	Dead	10,840	483	1.3	26	10	12.0	22	18.5
60	Bucking	430	18.8	0.66	26	9.9	19	26	21.5
60	Dead	11,330	475	0.66	25	8.5	21	28	23.0
60	Bucking	430	22.5	0.50	25.5	9.2	32	37	31
60	Dead	10,700	570	0.50	27.0	8.1	32	38	31

All rises in deg. cent. above temperature of ingoing water.

(1.22 by 3.3 mm.) copper, respectively. The 115-turn coil was used as primary and the other coil as secondary. This gives a transformer with very high reactance and accentuates the difference between the impedance watts and the $I^2 R$ watts. Table VII shows the losses as measured by core loss and impedance tests and also as measured by the input-output method. The $I^2 R$ loss + core loss in this case is 97 watts, but the impedance loss + core loss is 398 watts, which figure is closely checked by the input-output test.

Finally, the tests made on an induction regulator are given. The movable core contained a primary (shunt) winding and a short-circuited winding arranged at right angles to the shunt

winding. The secondary (series) winding was on the stationary core. The short-circuited winding consisted of copper bars of large cross-section, thereby naturally giving considerable eddy current losses.

Tests were made with the rotor in two different positions, first the position of maximum boost, which is obtained when the rotor is at one of the limit positions, second at the position of maximum impedance volts, which was found by trial. Table VIII gives the readings of core loss and impedance loss, calculated $I^2 R$ loss, loss by the input-output method and results of heat runs in the two positions. The heat runs were made

TABLE VII

COMPARISON OF LOSSES BY INPUT-OUTPUT AND IMPEDANCE METHODS SMALL HIGH-REACTANCE TRANSFORMER, RATED 60 CYCLES, 110 VOLTS PRIMARY, 50 AMPERES SECONDARY

Core loss			Impedance			Total loss
Volts	Amperes	Watts	Volts	Amperes	Watts	
110	21	48	60	21	350	398
Input			Output			
Volts	Amperes	Watts	Volts	Amperes	Watts	
110	21.8	2017	37.25	50	1630	387
Check 110		2020		50	1644	376
					Average	382

I^2R loss = 49.1 watts
Core loss = 48 "
Total 97.1 "

with the regulator operating as a transformer, the shunt winding being excited and the series winding loaded on a water box.

The difference in heating with the two connections is practically proportional to the difference in total loss.

We may conclude from the tests recorded that the total losses present when the transformer is under load are found by the addition of the no-load losses at normal volts to the impedance loss at normal current, the difference between the impedance losses and the $I^2 R$ loss representing the stray loss.

With transformers of ordinary reactance, the power factor of the impedance reading is sufficiently high (20 to 60 per cent)

to leave no question of the accuracy of the wattmeter reading. In the high-reactance transformers, the power factor in some cases is under 10 per cent, and here the wattmeter readings may be somewhat inaccurate.

The loss due to eddy current in the copper is given by a formula of the form

Eddy current loss = (frequency)^2 × (density of leakage flux)^2 × (width of conductor)^2 × a constant.

That is, the eddy current loss is proportional to the square of

TABLE VIII

LOSSES AND HEAT RUNS

INDUCTION REGULATOR, 55 KV-A., 2200 VOLTS PRIMARY, 125 AMPERES SECONDARY, OPERATED AS A TRANSFORMER

Losses	Maximum boost position	Maximum impedance position
Core loss	877	877
Impedance loss	705	1060
	1582	1937
Primary I^2R at 25 deg. cent.	302	110
Secondary " 25 " "	393	393
Short-circuit winding I^2R	0	160
Core loss	877	877
	1572	1540
Total loss, input-output method	1550	2000
Heat run		
Rise primary above 25 deg. cent.	34	39
" secondary " " " "	30	36
" top oil " " " "	30	35
" tank top " " " "	22	29
" tank bottom " " "	14	18

the frequency, the square of the maximum density of the leakage flux, and the square of the width of conductor at right angles to the leakage field. There is also an eddy current and hysteresis loss in the steel of the core cut by the flux in the impedance test, which is small and is not present as a separate loss when the transformer is under load.

The eddy current loss in the copper can be diminished by reducing the reactance, by reducing the width of copper at right angles to the flux, or by twisting the copper. These losses, however, are bound to exist to a certain extent even in the best-

designed transformers, and they are unavoidable in transformers that are purposely designed with high reactance. Their value (plus the other stray losses) may be found, as shown above, by subtracting, from the value of the short-circuit watts, the I^2r watts at the proper temperature.

II. Dielectric Losses

In ordinary power transformers the dielectric losses are usually negligible, but in high-voltage testing transformers they may form a large part of the total no-load losses. For a given dielectric at a constant temperature, an equation of this form gives the losses:

$$\text{Dielectric loss} = \text{frequency} \times \text{electrostatic capacity} \times (\text{voltage})^2 \times \text{a constant},$$

TABLE IX

DIELECTRIC LOSSES

TRANSFORMER 3750 KV-A., 120,000 VOLTS HIGH-TENSION, 12,000 VOLTS LOW-TENSION

High-tension in series			High-tension disconnected			Dielectric loss watts
Kilovolts high-ension by ratio	Amperes low-tension	Watts loss	Kilovolts high-tension by ratio	Amperes low-tension	Watts loss	
60	2.40	9100	60	2.3	8660	440
90	6.75	18450	90	6.6	17850	600
120	23.4	30400	120	24.0	29050	1350
132	43.0	42200	132	41.3	38100	4100

High-tension winding disconnected in middle. Oil temperature 30 deg. cent. (See Fig. 3.)

the constant depending upon the properties of the dielectric. In addition to the above there is also a small loss due to current leaking through the resistance of the insulation.

Table IX and Fig. 3 show the results of a test made on a shell-type transformer rated 60 cycles, 3750 kv-a., 12,000 volts low-tension, 120,000 volts high-tension. Losses were measured on the low-tension side, first with all the high-tension coils in series, and second, with the high-tension winding open at the middle. The difference between the readings represents the greater part of the dielectric loss. If the windings could be further subdivided, a still further reduction in the loss would

result. It will be seen that only above the operating voltage does the loss in the dielectric become appreciable.

Some tests were made on a testing transformer rated 60 cycles 100 kv-a., 500/1000/2000 volts low-tension, 200,000 volts high-tension. This transformer is of the type described by Mr. A. B. Hendricks, Jr., in his paper on *High-Tension Testing of Insulating Materials* (TRANSACTIONS, A. I. E. E., 1911, XXX, I, p. 167). A voltmeter coil of 40 turns is placed at the middle of the high-tension winding, and one end of this coil is connected to the neutral of the high-tension winding and to the ground. The coil is provided with taps at the 10th and 20th turns. The voltage across the whole coil is 400 volts when the transformer is normally excited.

An ammeter and wattmeter placed in the high-tension

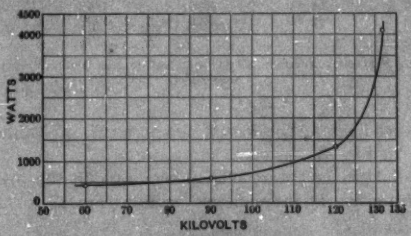


FIG. 3—DIELECTRIC LOSS, 3750-KV-A., 120-KV. TRANSFORMER
See Table IX.

circuit next to the ground enabled a measurement of the high-tension losses to be taken, at least such of them as are caused by the current measured in the high-tension winding. A 0.2-ampere, 30-volt wattmeter, with the potential coil in series with a multiplier and placed across the 10-turn voltmeter coil, was used. The readings obtained were small, and the total multiplying factor high, so that great accuracy cannot be claimed for the results. This method of measuring takes no account of the loss in the insulation between turns, but only that between high-tension and ground. Table X shows the losses at oil temperatures of 23 deg. cent. and 56 deg. cent., respectively. The difference between the total losses and the loss measured on the high-tension side decreases with increase in temperature, much more rapidly than we should expect

from a decrease in core loss alone (core loss decreasing about one per cent for each 10 deg. increase in temperature).

Table XI shows another set of readings taken at various air temperatures from −10 to 22 deg. cent. The results of Table X

TABLE X

NO-LOAD LOSS

TRANSFORMER 100 KV-A., 500/1000/2000 VOLTS TO 200,000 VOLTS

Kilovolts high-tension	Amperes low-tension	Total loss watts	High-tension loss watts	Temperature of top oil
100	0.87	682	132	23 deg. cent.
150	1.29	1394	294	
200	1.80	2356	543	
100	1.13	940	440	56 deg. cent.
150	1.68	2086	1174	
200	2.22	3620	2128	

Connected for 2000 volts low-tension, 200,000 volts high-tension. Measurements at 60 cycles. (See Fig. 4)

and the readings at the lowest temperature of Table XI are plotted in Fig. 4.

Table XII gives the results of readings on the low-tension and high-tension at frequencies varying from 47 to 115 cycles

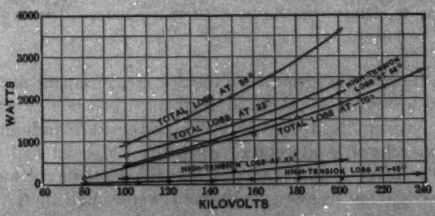


FIG. 4—NO-LOAD LOSSES, 100-KV-A., 200-KV. TRANSFORMER
See Table X.

per sec. These results are plotted in Fig. 5. The high-tension losses increase somewhat with the frequency, but not directly. On account of the preponderance of the core loss, the total losses decrease with increase in frequency, and consequent decrease in flux density in the iron.

TABLE XI

NO-LOAD LOSSES—EFFECT OF TEMPERATURE
TRANSFORMER 100 KV-A., 500/1000/2000 VOLTS TO 200,000 VOLTS

Kilovolts high-tension by ratio	Amperes low-tension	Watts low-tension	Kilovolts high-tension	Amperes high-tension	Watts high-tension	Temperature air deg. cent
90		120	80.5	0.0051	10	—10
101		550	105.6	0.0068	20	
120		650	120	0.008	40	
140		900	140.5	0.0093	60	
160		1150	159	0.0106	90	
180.4		1550	181	0.0124	120	
200.6		1900	201	0.0134	140	
221		2300	221	0.0156		
238		2650	237	0.0178	220	
129.6		850	129	0.0087	80	—2
142.6		950	142	0.0095	90	
162.2		1300	162	0.0109	120	
185.4		1650	186	0.0131	150	
203		1900	203	0.0145	200	
226		2450	224.6	0.0165	250	
110		550	111.5	0.0077	50	0
154.4		1100	153	0.0105	110	
200		1850	200	0.0143	180	
50		100	50	—	5	3
64		240	65.5	—	15	
76		260	75.5	0.0052	20	
114		600	113	0.008	80	
135		850	134	0.009	100	
177.4		1450	187	0.0123	160	
192.6		1750	193	0.0136	200	
210.8		2200	210	0.0154	240	
233.2		2600	231	0.0168	280	
80	1.14	400	80	0.005	55	13
100	1.37	620	100.5	0.007	100	
120	1.63	820	121.5	0.008	150	
143.6	1.87	1180	143.5	0.010	210	
162.4	2.05	1450	161.0	0.011	280	
181.0	2.29	1800	181.0	0.013	350	
203	2.69	2200	202.2	0.015	440	
219	3.25	2640	217.0	0.016	540	
235	4.20	3050	234.0	0.017	660	
158.8	2.10	1500	158.4	0.0117	360	19
181	2.36	1900	180.0	0.0137	480	
202.8	2.78	2340	201.2	0.0152	600	
80	1.18	470	80	0.0057	80	22
90.2	1.28	570	91	0.0065	97	
100.2	1.42	670	100.6	0.0071	110	
120.4	1.65	925	119.3	0.0084	190	
142.4	——	1250	141.0	0.01	270	
160.0	2.15	1550	159.0	0.0117	370	
180.0	2.40	1900	179.6	0.0135	460	
202.2	2.70	2550	201.2	0.0155	600	

Connected 1000 volts low-tension, 200,000 volts high-tension. All measurements at 60 cycles.
(See Fig. 4)

TABLE XII

NO-LOAD LOSSES—EFFECT OF FREQUENCY

TRANSFORMER 60 CYCLES, 100 KV-A., 500/1000/2000 VOLTS LOW-TENSION, 200,000 VOLTS HIGH-TENSION

Frequency cycles per per sec.	High-tension kilovolts by ratio	Low-tension amperes	Low-tension watts	High-tension kilovolts	High-tension amperes	High-tension watts	Air temperature deg. cent.
47	120	1.72	930	120	0.0065	100	12
	140.4	2.11	1200	139	0.0078	180	
	162.2	3.00	1600	162	0.0088	220	
	182.8	4.69	2050	184	0.0101	300	
	201			201	0.011	350	
	211			210	0.012	400	
57	122.2	1.56	880	121	0.0085	100	12
	141.2	1.78	1150	140	0.0091	150	
	162.4	2.00	1430	161.6	0.0107	240	
	181.8	2.33	1800	182.0	0.0126	300	
	203	3.00	2200	203.2	0.0141	350	
	215	3.71	2500	213.6	0.0151	440	
70	120	1.61	770	119	0.0095	120	12
	142.4	1.91	1100	141.4	0.0118	200	
	158.4	2.12	1340	160	0.0135	250	
	180.6	2.32	1650	180.6	0.0155	300	
	203	2.95	2010	203.6	0.0175	400	
	221	2.68	2400	221.6	0.0188	500	
80	122	1.81	770	121.6	0.0113	150	12
	140.4	2.10	990	140.6	0.135	200	
	160.2	2.41	1290	159.6	0.0159	250	
	179.4	2.64	1550	179.0	0.0175	300	
	201	2.96	1900	201.0	0.0193	440	
	225	3.26	2350	223.2	0.0219	550	
90	122.2		700	121	0.13	140	14
	139.2		850	139	0.015	200	
	162.6		1100	162.4	0.018	300	
	180.6		1400	180.6	0.020	400	
	201.0		1750	202	0.022	560	
	221		2200	221.2	0.025	650	
115	121		700	121.6	0.017	140	14
	142.4		850	142.6	0.0195	250	
	160.4		1100	160.0	0.0221	300	
	180.6		1450	181.0	0.0248	400	
	201.0		1650	201	0.0277	550	
	223.2		2200	223.2	0.312	700	

Connected for 1000 volts low-tension, 200,000 volts high-tension (See Fig. 5).

In Table XIII are given the results of an 11½-hour heat run at normal voltage, open circuit. During this time the temperature at the top of the oil rose 35 deg. cent. above its initial

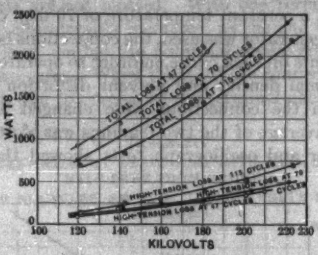


FIG. 5—NO-LOAD LOSSES, 100-KV-A., 200-KV. TRANSFORMER
See Table XII.

temperature, the total losses increased 62 per cent and the high-tension losses increased 263 per cent. Losses are plotted against increase of temperature and increase of high-tension loss against

TABLE XIII

NO-LOAD LOSSES—VARIATION WITH TEMPERATURE

TRANSFORMER 60 CYCLES, 100 KV-A., 500/1000/2000 VOLTS TO 200,000 VOLTS

Hours heat run	Deg. cent. rise oil	Total watts loss	Low-tension amperes	High-tension loss	High-tension amperes	Increase in high-tension loss
0	0	2234	1.74	587	0.02	0
1	4	2268	1.75	587	0.02	0
2	7.2	2346	1.76	660	0.02	73
3	10.8	2424	1.77	734	0.02	147
4	14	2508	1.81	880	0.02	293
5	17	2610	1.83	1027	0.02	440
6	20.2	2774	1.88	1174	0.02	587
7	23	2920	1.92	1321	0.023	734
8	26	3040	1.97	1468	0.023	881
9	28.5	3184	2.0	1614	0.025	1027
10	31	3326	2.1	1761	0.025	1174
11	34	3560	2.2	2055	0.025	1468
11.5	35	3620	2.22	2128	0.025	1541

Rises above 21 deg. cent., initial oil temperature.

Transformer connected for 2000 volts low-tension, 200,000 volts high-tension. (See Fig. 6.)

increase of temperature, in Fig. 6. It will be seen from this that the loss goes up about as the square of the deg. cent. increase in temperature.

A series of tests was conducted on a testing transformer, No. 630263, rated 60 cycles, 500 kv-a., 1100/2200 volts low-tension, 750,000 volts high-tension. To eliminate the effect of variations in temperature, the oil was kept circulating and maintained at a constant temperature of 70 deg. cent. A 500-kw., 60-cycle generator was used, the connections being changed at various points on each curve, in order to operate the machine at nearly normal density and prevent distortion of the wave shape. When the connections were changed and readings repeated, an average of the two readings was plotted.

Phase meter and oscillograph tests showed the current to

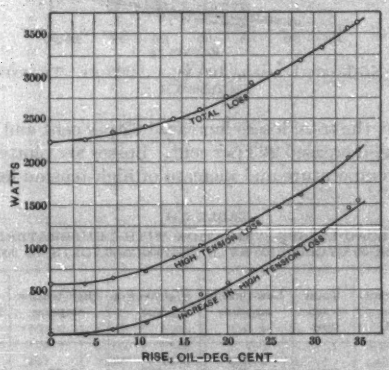


FIG. 6—NO-LOAD LOSSES, 100-KV-A., 200-KV. TRANSFORMER
See Table XIII.

be leading at all voltages, except the very low ones (under 100 kv.) where the power factor approaches unity.

Losses were measured on the low-tension side only. The following curves were taken:

1. Without leads
   a. Middle of high-tension winding grounded.
   b. High-tension not grounded.
   c. One end of high-tension grounded.
2. With leads.
   a. Middle of high-tension grounded.
   b. High-tension not grounded.
   c. One end of high-tension grounded.

The results are given in Tables XIV to XIX inclusive, and plotted in Fig. 7. As the losses with the winding not grounded are practically the same as the losses with the middle grounded, the latter tests are not plotted. With one terminal grounded the losses are considerably increased, as the end of the winding in this case is at double the potential above ground that it is in the first two cases. When the leads are connected, the losses are increased, due to corona on the terminal choke coils and to

TABLE XIV

NO-LOAD LOSSES—WITHOUT LEADS AND WITH HIGH-TENSION TERMINALS FREE FROM GROUND

TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 VOLTS TO 750,000 VOLTS NO. 630,263

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Generator connection
50	146	2.34	308	440-volt
100	295	4.5	1,185	
150	441	6.2	2,510	
150	441	5.98	2,510	1150-volt
200	586	7.87	4,220	
300	881	11.4	9,110	
350	1028	13.3	12,370	
375	1100	14.1	14,180	
400	1173	15.2	16,180	
450	1320	17.1	20,450	
375	1100	14.7	14,220	2300-volt
400	1173	15.5	16,200	
450	1320	17.4	20,400	
500	1467	19.4	25,100	
550	1614	21.7	30,150	
600	1760	24.8	36,100	
650	1910	29.0	42,800	
700	2060	36.3	50,100	
750	2200	46.5	59,200	

Temperature of oil 70 deg. cent. Connected on low-tension for 2200 volts. (See Fig. 7.)

the boost in high-tension voltage caused by the capacity of the leads. Even without leads, there is considerable boost in voltage, as may be judged from the fact that with center of high-tension winding grounded, a voltage of 650 kv. by ratio caused a discharge across a needle spark gap of 75.5 in. (192 cm.), equivalent approximately to 750,000 volts; and with one terminal grounded, a voltage by ratio of 375,000 caused the discharge of a 50.5-in. (128-cm.) gap, equivalent to 500,000 volts

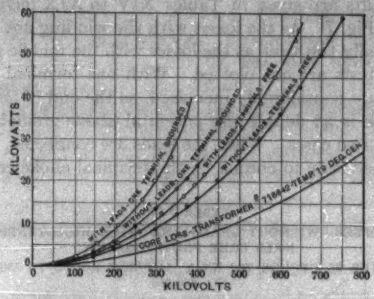


FIG. 7—NO-LOAD LOSSES, TEMPERATURE 70 DEG. CENT., 500-KV-A., 750,000-VOLT TRANSFORMER, NO. 630263

See Tables XIV to XIX.

(Shows core loss of transformer No. 716642 at 19 deg. cent.)

TABLE XV

NO-LOAD LOSSES—WITHOUT LEADS AND WITH ONE HIGH-TENSION TERMINAL GROUNDED

TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 TO 750,000 VOLTS. NO. 630,263

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Current high-tension to ground	Generator connection
		Left-hand leg, facing high-tension, grounded			
50	146	3.29	416	—	440-volt
100	292	7.58	1,526	—	
150	442	11.9	3,500	—	
150	442	12.3	3,490	—	1150-volt
200	588	16.5	5,980	0.053	
250	732	20.9	9,240	0.084	
300	881	25.1	13,510	0.091	
350	1028	29.1	18,390	0.107	
375	1100	31.2	20,900	0.115	
400	1175	32.8	23,800	0.122	
450	1320	Arcs to ground			
		Right-hand leg, facing high-tension, grounded			
300	881	26.1	13,820	0.093	1150-volt
350	1028	30.3	18,900	—	
375	1100	32.3	21,400	0.112	
400	1173	34.7	24,600	0.118	
425	1247	Arcs to ground			

Temperature of oil 70 deg. cent. (See Fig. 7)

Some tests were also made on a companion transformer, No. 716642, which is identical with the transformer just described except that the low-tension voltage is 2500. The loss was first measured with the low-tension coils only on core, thus giving the core loss alone. The high-tension coils were then assembled on core, but left totally disconnected from each other. This high-

TABLE XVI

NO-LOAD LOSSES—WITHOUT LEADS AND WITH MIDDLE OF HIGH-TENSION WINDING GROUNDED

TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 to 750,000 VOLTS. NO. 630,263

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Generator connection
50	146	2.35	313	440-volt
100	295	4.44	1,240	
150	441	6.30	2,550	
150	441	6.03	2,520	1150-volt
200	586	7.94	4,280	
250	732	9.78	6,520	
300	881	11.7	9,300	
350	1028	13.5	12,590	
375	1100	14.3	14,310	
400	1173	15.2	16,300	
450	1320	17.0	20,700	
500	1467	18.8	25,700	
300	881	12.0	9,230	2300-volt
350	1028	13.8	12,510	
375	1100	14.8	14,220	
400	1173	15.4	16,320	
450	1320	17.2	20,500	
500	1467	19.1	25,250	
550	1614	21.7	30,800	
600	1760	24.8	36,700	
650	1910	29.4	43,100	
700	2060	36.8	50,400	
750	2200	45.7	59,300	

Temperature of oil 70 deg. cent.

tension winding consists of 134 coils, with a total of 26,000 turns. The volts per coil are about 2850 and the volts per layer 28½. The loss in each case was measured on the low side, and is therefore the core loss plus the dielectric loss. It is evident that the greater part of the dielectric loss is present, even with all the coils disconnected.

TABLE XVII

NO-LOAD LOSSES—LEADS CONNECTED AND HIGH-TENSION WINDING UNGROUNDED

TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 TO 750,000 VOLTS. NO. 630,263.

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Generator connection
52.2	153	2.73	415	440-volt
104.4	306	5.29	1,560	
157.0	460	8.14	3,360	
157	460	7.92	3,270	1150-volt
209	613	10.7	5,540	
261	766	13.2	8,320	
314	920	15.8	12,500	
367	1074	18.3	16,600	
392	1150	19.5	19,050	
418	1226	20.9	22,700	
506	1484	25.1	33,000	1535-volt
554	1625	27.0	38,800	
586	1720	29.0	44,900	
636	1864	32.4	53,700	
646	1895	33.2	56,100	

Temperature of oil 70 deg. cent. (See Fig. 7)

TABLE XVIII

NO-LOAD LOSSES—LEADS CONNECTED AND ONE HIGH-TENSION TERMINAL GROUNDED

TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 TO 750,000 VOLTS. NO. 630,263

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Generator connection
52.2	153	5.19	638	440-volt
104.4	306	11.4	2,470	
157	460	18.1	5,550	
157	460	18.7	5,450	1150-volt
209	613	25.1	9,820	
266	772	32.7	15,700	
297	875	37.2	20,100	
335	982	41.9	25,700	
370	1087	46.1	35,400	
376	1102	47.5	38,300	

Temperature of oil 70 deg. cent. (See Fig. 7)

TABLE XIX
NO-LOAD LOSSES—LEADS CONNECTED AND MIDDLE OF HIGH-TENSION WINDING GROUNDED
TRANSFORMER 60 CYCLES, 500 KV-A., 1100/2200 to 750,000 VOLTS. NO. 630,263

Kilovolts high-tension by ratio	Volts low-tension	Amperes low-tension	Watts	Generator connection
177.5	497	8.91	3,350	1150-volt
327	916	16.9	11,420	
333	978	18.5	13,010	
417	1222	24.4	20,870	
502	1472	28.45	30,600	

Temperature of oil 70 deg. cent.

The transformer was next tested completely assembled and ready for service. The difference between this loss and the core loss, we may take as the dielectric loss under normal conditions. Another set of readings was taken with one high-tension terminal grounded. These curves are plotted in Fig. 8, and the readings are given in Tables XX to XXIII, inclusive.

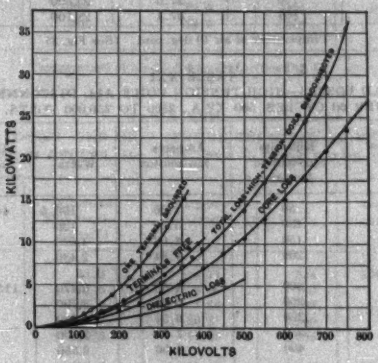


FIG. 8—NO-LOAD LOSSES, 500-KV-A., 750,000-VOLT TRANSFORMER, NO. 716642
See Tables XX to XXIII.

For comparison the core loss curve of Fig. 8 is reproduced in Fig. 7. The difference between the total loss curves of Fig. 7 and the core loss curve is greater than the difference between the same curves of Fig. 8, due to the higher temperature in the first case.

TABLE XX
CORE LOSS—LOW-TENSION COILS ONLY ON CORE
TRANSFORMER 60 CYCLES, 500 KV-A., 2500 TO 750,000 VOLTS. NO. 716,642.

Low-tension volts	Kilovolts high-tension by ratio	Amperes low-tension	Watts	Generator connection
166	50	2.24	165	440-volt
333	100	3.04	607	
499	150	3.70	1,234	
499	150	3.71	1,234	1150-volt
666	200	4.35	2,025	
833	250	4.95	3,030	
1000	300	5.64	4,180	
1166	350	6.45	5,360	
1166	350	5.45	5,350	1535-volt
1335	400	7.29	7,070	
1500	450	8.34	8,830	
1670	500	9.45	10,550	
1835	550	11.5	12,900	
1835	550	11.5	12,900	2300-volt
2000	600	13.7	15,150	
2165	650	17.0	17,760	
2330	700	21.5	20,950	
2500	750	27.5	23,600	
2680	804	37.4	28,100	

Temperature of air 19 deg. cent. (See Fig. 8)

TABLE XXI
NO-LOAD LOSSES—HIGH-TENSION COILS ALL DISCONNECTED
TRANSFORMER 60 CYCLES, 500 KV-A., 2500 TO 750,000 VOLTS. NO. 716,642

Low-tension volts	Kilovolts high-tension by ratio	Amperes low-tension	Watts	Generator connection
166.5	50	2.36	196.5	440-volt
333	100	3.30	720	
500	150	4.08	1,520	
666	200	4.84	2,480	
666	200	4.80	2,470	1150-volts
833	250	5.66	3,790	
1000	300	6.54	5,280	
1165	350	7.60	7,100	
1334	400	9.00	9,550	
1250	375	8.37	8,430	2300-volt
1334	400	8.79	9,210	
1500	450	10.4	11,350	
1666	500	12.2	13,800	
1835	550	14.3	17,250	
2000	600	17.2	20,660	
2170	650	20.7	24,560	
2330	700	25.0	28,710	
2500	750	30.7	35,720	

Temperature of air 19 deg. cent. (See Fig. 8)

TABLE XXII

NO-LOAD LOSSES—TERMINALS FREE FROM GROUND

TRANSFORMER 60 CYCLES, 500 KV-A., 2500 TO 750,000 VOLTS. NO. 716,642

Low-tension volts	Kilovolts high-tension by ratio	Amperes low-tension	Watts	Generator connection
200	60	1.66	322	384-volt
242	72.5	2.03	466	
252	75.5	2.11	500	
292	87.5	2.55	648	
314	94.2	2.7	748	
324	97.2	2.91	791	
346	104	3.18	900	
420	126	3.99	1250	767-volt
540	162	5.28	1965	
705	212	7.1	3160	
762	229	7.86	3662	
814	244	8.35	4145	
823	247	8.5	4120	1150-volt
1026	308	10.7	6360	
1223	366	13.0	8830	
1291	388	13.7	9860	

Temperature of air 25.5 deg. cent. (See Fig. 8)

TABLE XXIII

NO-LOAD LOSSES—ONE HIGH-TENSION TERMINAL GROUNDED

TRANSFORMER 60 CYCLES, 500 KV-A., 2500 to 750,000 VOLTS. NO. 716,642

Low-tension volts	Kilovolts high-tension by ratio	Amperes low-tension	Watts	Generator connection
212	63.6	4.71	524	384-volts
255	76.5	6.06	740	
312	93.6	7.60	1,102	
400	120.0	10.2	1,740	
455	136.5	11.85	2,235	
608	182.5	16.4	3,880	767-volts
675	202.0	18.5	4,890	
750	225.0	20.8	5,950	
825	248.0	23.3	7,250	
758	228	21.3	6,080	1150-volts
900	270	26.3	8,720	
960	288	28.5	9,860	
1050	315	31.0	11,900	
1180	354	35.5	15,300	

Temperature of air 22.5 deg. cent. (See Fig. 8)

As the insulation losses in all cases are included in the no-load readings, no especial determination of them is necessary, but it is apparent that it is essential to measure the no-load losses at the operating temperature.

III. Recommendations

It is recommended that Sections 156 to 159 of the Standardization Rules be amended as follows:

The losses in Transformers are:

1 No-Load Losses, including Core Loss and Dielectric Loss, measured with open secondary circuit, at rated frequency and rated (full-load) voltage minus $I\,r$, where I = rated current, and r = resistance of primary circuit. There is also a small resistance loss due to exciting current in the primary.

a. Core Loss, including hysteresis loss and loss due to eddy currents in the steel.

b. Dielectric Loss, energy loss in the insulation due to electrostatic stress.

2 Load Losses, including Resistance Loss and Stray Loss, practically equal to the impedance losses which are determined by short-circuiting the secondary and impressing upon the primary a voltage sufficient to send rated load current through the transformer.

a. Resistance Loss, the sum of the I^2r losses in the primary and secondary windings of a transformer, or in the two sections of the winding of an auto-transformer, where I = rated load current in the winding or section of winding, and r = resistance. In the primary, I = resultant of load current and exciting current.

b. Stray Loss, the eddy current loss in the copper, and the stray losses in the neighboring iron, due to the stray or leakage flux caused by the current at rated load.

3 On account of the variation with temperature, all losses should be measured at the operating temperature.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

STRAY LOSSES IN TRANSFORMERS

BY C. FORTESCUE AND W. M. McCONAHEY

(1) Introduction

The object of this paper is to obtain a convenient method of evaluating the actual losses in the copper of a transformer under operating conditions, and of figuring the regulation.

The losses in the copper of a transformer are influenced by several conditions, namely,

a. Frequency and wave form

b. Dissymmetry of winding

c. Permeability of iron

d. Temperature.

a. The portion of the losses in the copper that depends on frequency is included in what is termed "eddy-current loss in the copper," analogous to "skin effect" in line conductors, and is practically eliminated in careful designs. Higher harmonics in the wave form of impressed e.m.f. have also some effect on these losses, as would naturally be expected, since they are dependent upon frequency.

b. The losses due to dissymmetry of winding are confined to transformers with parallel connections when the different circuits forming the parallel-connected secondary are not similarly disposed with regard to the primary circuit and one another. These losses are independent of frequency and are of little importance, since they will be negligibly small in good designs.

c. The losses in the copper may be affected by the permeability of the iron. If eddy-current losses are present these will be affected by any change in the leakage induction due to a change of permeability. The permeability will affect the value of the exciting current and thereby the copper loss under load. These

effects are, however, usually so small as to be negligible except in special cases.

d. Temperature will have the effect of increasing the true I^2R losses and decreasing the eddy-current losses. Where a transformer has large eddy-current losses its copper loss should be measured if possible at the temperature on which guarantees are based. A first approximation to the effect of temperature on eddy-current losses may be obtained by considering them directly proportional to the conductivity of the copper and correcting for temperature accordingly.

(2) Theoretical Study of Copper Losses in Transformers

The theory of the transformer depends on that of two mutually inductive circuits. A clear understanding of the actions that take place in transformers cannot be obtained without a careful study of the theory of such a pair of circuits. It must not be supposed, however, that a system of this kind can be made to represent a transformer exactly; on account of the peculiar characteristics of iron this is impossible. It furnishes, however, a model sufficiently close to be accurate enough for all practical purposes. The resistances and inductances of the two circuits will be influenced by frequency, temperature, etc. in the same way as the windings of a transformer. Results obtained mathematically for such a pair of circuits will apply with almost equal accuracy to transformers.

Let the resistance and inductance of the primary circuit be R_1 and L_1 and those of the secondary R_2 and L_2; let the mutual inductance be M and the resistance and self-inductance of the load on the secondary circuit be R_0 and L_0; let e_1 be the value of the impressed e.m.f. The differential equations of the two circuits are

$$L_1 \frac{d i_1}{d t} + M \frac{d i_2}{d t} + R_1 i_1 = e_1 \tag{1}$$

$$(L_2 + L_0) \frac{d i_2}{d t} + M \frac{d i_1}{d t} + (R_2 + R_0) i_2 = 0 \tag{2}$$

From (2) we have

$$i_2 = - \frac{M \dfrac{d}{d t}}{(R_2 + R_0) + (L_2 + L_0) \dfrac{d}{d t}} i_1 \tag{3}$$

Substituting this in (1)

$$\left(L_1 \frac{d}{d\,t} - \frac{M^2 \dfrac{d^2}{d\,t^2}}{(R_2 + R_0) + (L_2 + L_0) \dfrac{d}{d\,t}} + R_1 \right) i_1 = e_1$$

or

$$\left\{ R_1 - \frac{M^2 \dfrac{d^2}{d\,t^2}}{(R_2 + R_0)^2 - (L_2 + L_0)^2 \dfrac{d^2}{d\,t^2}} (R_2 + R_0) \right.$$

$$\left. + \left(L_1 + \frac{M^2 \dfrac{d^2}{d\,t^2}}{(R_2 + R_0)^2 - (L_2 + L_0)^2 \dfrac{d^2}{d\,t^2}} (L_2 + L_0) \right) \frac{d}{d\,t} \right\} i_1 = e_1 \qquad (4)$$

If e_1 be a harmonic function of time it may be represented by the real part of the complex variable function

$$\Sigma \left\{ (a_n + j\,b_n)\, e^{j\,n\,p\,t} \right\}$$

The final or steady value of i_1 will then be the real part of the similar expression afforded by the particular integral of equation (4); or, denoting the complex variable function representing in its real part the value of i_1 by $\check{I}_1$ we have equations (5) and (6).

$\check{E}_1$ represents the complex variable function the real terms of which give the instantaneous value of e_1 and $\hat{Z}_a$ represents the operation $R_a + j\,n\,p\,L_a$ on each successive term of the quantities $\check{I}_1$ and $\check{E}_1$, the value of n being the same as that in the index of the base of the Napierian logarithm contained in the term operated on. The values of R_a and L_a will be

$$R_a = R_1 + \frac{n^2\,p^2\,M^2}{(R_2 + R_0)^2 + n^2\,p^2\,(L_2 + L_0)^2} (R_2 + R_0) \qquad (7)$$

$$L_a = L_1 - \frac{n^2\,p^2\,M^2}{(R_2 + R_0)^2 + n^2\,p^2\,(L_2 + L_0)^2} (L_2 + L_0) \qquad (8)$$

$$\check{I}_1 = \Sigma \left\{ \frac{(a_n + j\,b_n)\,e^{j\,n\,p\,t}}{R_1 - \dfrac{M^2 \dfrac{d^2}{d\,t^2}}{(R_2 + R_0)^2 - (L_2 + L_0)^2 \dfrac{d^2}{d\,t^2}} (R_2 + R_0) + \left(L_1 + \dfrac{M^2 \dfrac{d^2}{d\,t^2}}{(R_2 + R_0)^2 - (L_2 + L_0)^2 \dfrac{d^2}{d\,t^2}} (L_2 + L_0) \right) \dfrac{d}{d\,t}} \right\}$$

$$= \Sigma \left\{ \frac{(a_n + j\,b_n)\,e^{j\,n\,p\,t}}{R_1 + j\,n\,p\,L_1) + \dfrac{n^2\,p^2\,M^2}{(R_2 + R_0)^2 + n^2\,p^2\,(L_2 + L_0)^2} \left\{ (R_2 + R_0) - j\,n\,p\,(L_2 + L_0) \right\}} \right\} \tag{5}$$

$$= \frac{\check{E}_1}{\hat{Z}_a} \tag{6}$$

This gives the effective resistance and inductance of the primary circuit with loaded secondary to the nth harmonic component of the impressed e.m.f.

Using the same notation, equation (3) may be put into the form

$$\check{I}_2 = -\frac{j\,n\,p\,M}{(R_2 + R_0) + j\,n\,p\,(L_2 + L_0)}\,\check{I}_1 \tag{9}$$

If the load resistance and inductance be made zero we shall have the effective resistance of the system under short circuit, that is,

$$R_b = R_1 + \frac{n^2\,p^2\,M^2}{R_2^2 + n^2\,p^2\,L_2^2}\,R_2 \tag{10}$$

$$L_b = L_1 - \frac{n^2\,p^2\,M^2}{R_2^2 + n^2\,p^2\,L_2^2}\,L_2 \tag{11}$$

Similarly, if the primary winding be short-circuited and the current circulated through the secondary, the effective resistance and inductance will be

$$R_c = R_2 + \frac{n^2\,p^2\,M^2}{R_1^2 + n^2\,p^2\,L_1^2}\,R_1 \tag{12}$$

$$L_c = L_2 - \frac{n^2\,p^2\,M^2}{R_1^2 + n^2\,p^2\,L_1^2}\,L_1 \tag{13}$$

The secondary terminal e.m.f. under load is

$$\check{E}_2 = \check{I}_2\,\hat{Z}_0 \tag{14}$$

The secondary e.m.f. at no load is

$$\check{E}_0 = -\frac{j\,n\,p\,M}{R_1 + j\,n\,p\,L_1}\,\check{E}_1 \tag{15}$$

by (6) this is

$$\check{E}_0 = -\frac{j\,n\,p\,M}{R_1 + j\,n\,p\,L_1}\,\check{I}_1\,\hat{Z}_a$$

and by (9) this is

$$\check{E}_0 = \frac{(R_2 + R_0) + j\,n\,p\,(L_2 + L_0)}{R_1 + j\,n\,p\,L_1}\,\check{I}_2\,\hat{Z}_a \tag{16}$$

From (14) and (16),

$$\check{E}_0 - \check{E}_2 = \check{I}_2\left\{\frac{(R_2 + R_0) + j\,n\,p\,(L_2 + L_0)}{R_1 + j\,n\,p\,L_1}\,\hat{Z}_a - \hat{Z}_0\right\}$$

or, substituting for $\hat{Z}_a$ and $\hat{Z}_0$,

$$\check{E}_0 - \check{E}_2 = \check{I}_2\left\{(R_2 + j\,n\,p\,L_2) + \frac{n^2\,p^2\,M^2}{R_1^2 + n^2\,p^2\,L_1^2}\,(R_1 - j\,n\,p\,L_1)\right\} \tag{17}$$

This latter expression gives the basis on which to calculate the regulation of transformers. For air coils having mutual inductance it gives exactly the same effective resistance and inductance as obtained with short-circuited primary and current circulated through the secondary. [See (12) and (13)]. With transformers where L_1 and L_2 are functions of the induction it gives the effective short-circuit resistance and inductance under load conditions, and these may be slightly different from those obtained with short circuit.

From (1) we obtain another expression for $\check{I}_1$

$$\check{I}_1 = \frac{\check{E}_1}{R_1 + j\,n\,p\,L_1} - \frac{j\,n\,p\,M}{R_1 + j\,n\,p\,L_1}\,\check{I}_2 \tag{18}$$

$$= \check{I}_m - \frac{j\,n\,p\,M}{R_1 + j\,n\,p\,L_1}\,\check{I}_2 \tag{19}$$

The first term is the open-circuit exciting current; the second term is the current obtained in the primary when it is short-circuited and current I_2 is sent through the secondary winding. If $|I_m|_n |I_1|_n$ and $|I_2|_n$ denote the effective values of the nth term of the series representing each of the quantities $\check{I}_m$ $\check{I}_1$ and $\check{I}_2$, and

if φ_n be the phase displacement between the nth harmonic of $\check{E}_1$ and $\check{I}_2$, we have from (19)

$$I_1^2 = \Sigma \{|I_1|_n^2\}$$

$$= I_m^2 + \Sigma \left\{ \frac{n^2 p^2 M^2}{R_1^2 + n^2 p^2 L_1^2} |I_2|_n^2 + 2 \frac{n\ p\ M}{\sqrt{R_1^2 + n^2 p^2 L_1^2}} |I_m|_n |I_2|_n \sin \varphi_n \right\} \quad (20)$$

The true copper loss is

$$I_1^2 R_a - I_2^2 R_0 = I_1^2 R_1 + I_2^2 R_2$$

$$= I_2^2 R_2 + \Sigma \left\{ \frac{n^2 p^2 M^2}{R_1^2 + n^2 p^2 L_1^2} |I_2|^2_n R_1 \right\}$$

$$+ 2 \Sigma \left\{ \frac{n\ p\ M}{\sqrt{R_1^2 + n^2 p^2 L_1^2}} |I_m|_n |I_2|_n R_1 \sin \varphi_n \right\} + I_m^2 R_1 \quad (21)$$

The first two values on the right-hand side of equation (21) is the copper loss as obtained from (18), which, as will be shown later, may be obtained by measurement. It will also be shown to be practically the same as the loss obtained under short circuit. The fourth term is constant for a given impressed e.m.f. and is included in the iron loss measurement. The third term is the correction to be made to the loss as obtained by (17) or the short-circuit method, to obtain the correct value of the copper loss. In practical application of this correction the quantity

$$\frac{n\ p\ M}{\sqrt{R_1^2 + n^2 p^2 L_1^2}}$$

may be taken to be equal to n_2/n_1 where n_1 and n_2 are the primary and secondary turns.

(3) Method of Measuring Impedance and Short-Circuit Loss under Load

It has been shown how the true copper loss in the case of two mutually inductive circuits may be obtained by a correction to be added to the copper loss obtained under short circuit. In transformers the old method of obtaining the short-circuit loss has been subjected to criticism on the ground that the condition

of the iron when the transformer is under load as regards permeability is very different from its condition when one winding is short-circuited and full-load current circulated through the other. Equation (**17**) furnishes us with a theoretical basis for obtaining the value of the short-circuit losses with conditions of induction obtained under operation. As regards mutually inductive circuits in air, the difference between the open-circuit voltage of the secondary and the full-load voltage as shown by (**17**) is the mathematical equivalent of the impedance voltage obtained with the primary short-circuited and full-load current circulated in the secondary winding. With transformers there is a difference between these two quantities, due to the permeability being differ-

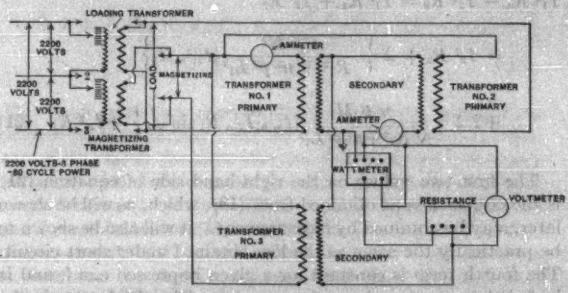


FIG. 1 —SCHEME OF CONNECTIONS FOR MEASURING COPPER LOSS AND IMPEDANCE VOLTS OF TRANSFORMER UNDER LOAD (OPPOSITION) AT DIFFERENT POWER FACTORS.

ent at high and low induction. Thus for transformers (**17**) gives the short-circuit impedance and short-circuit loss with the same induction in the iron as that obtained under load, while (**12**) and (**13**) give the resistance and inductance obtained under short circuit when the induction is very low.

With a view to determining whether the conditions in the iron produce an appreciable change in the values of the short-circuit losses of a transformer, the following method, based on equation (**17**), of measuring impedance volts and short-circuit losses with load conditions, was used. Two transformers were loaded by the opposition method. A third transformer of like characteristics was connected with its primary in multiple with that one of the two loaded transformers of which the short-circuit losses and impedance under load condition was to be measured. The

secondaries of the two transformers were connected so that the electromotive forces were opposed, and a wattmeter, the series coil of which was in the secondary circuit of the two loaded transformers, had its shunt energized by the difference of the secondary electromotive forces of the loaded and unloaded transformers. The wattmeter then, with proper corrections, reads the short-circuit loss corresponding to the condition of induction in the iron at the load that is given. The power factor of the load may be changed by exciting the loaded transformer from the different phases of a three-phase generator. (See Fig. 1.)

(4) Test Results

Tests were made on a 150-kv-a. 60-cycle transformer to ascertain if there were any variations in the values of the short-circuit losses under different power factors of load and change in excitation. The results obtained are tabulated. (See Table I.)

The first six results given in the table were obtained with exciting voltages 0, 500, 1000, 1500, 2000 and 2500; the losses being respectively 1164.4, 1164.4, 1164.4, 1169.4, 1176.4 and 1176.4 watts. The maximum variation in these values is a little over 1 per cent. The first value should be identical with the loss obtained by the short-circuit test, which is 1136 watts; it is seen to be 2½ per cent higher. This difference is partly due to a difference in temperature of the windings at the time the two tests were made and partly to a slight difference in the magnetic characteristics of the loaded and unloaded transformers. The remaining results show a difference in the measured values at full load, with power factors varying from 31 per cent to 99 per cent, of a little over 2 per cent. This difference is due entirely to the rise in temperature of the windings during test. This also is the cause of the difference between the value at zero excitation and that at maximum excitation and 31 per cent power factor. The principal results of these tests are given below.

Short-circuit loss obtained by standard method.....	1136
" " " by method described, exciting volts zero.....	1164
" " " maximum excitation, 31 per cent power factor.....	1175.4
" " " " " 99 per cent power factor.....	1189.4

Tests were made on a transformer of smaller size with similar results.

(5) Practical Formulas

The following formulas are based on the preceding investigation.

Regulation

$$I\,R = \frac{\text{short-circuit losses}}{\text{rated output}} \times 100$$

$$I\,X = \frac{\text{reactance volts}}{\text{scondary rated voltage}} \times 100$$

$P.F.$ = Power factor of load.

Per cent regulation $= (P.F.)\,I\,R + \sqrt{1-(P.F.)^2}\;I\,X$ **(22)**

The following correction may be added where a higher degree of accuracy is required.

$$\text{Correction} = \frac{\{(P.F.)IX - \sqrt{1-(P.F.)^2}\,I\,R\}^2}{200} \qquad \textbf{(23)}$$

$I^2\,R$ and Stray Losses in Copper

If we define:

I_m = effective value of primary no-load, exciting current
I_2 = effective value of secondary load current
n_1 = number of primary turns
n_2 = number of secondary turns
R_1 = effective resistance of primary winding,

$$p = \frac{n_1\,I_m}{n_2\,I_2}$$

$$q = \frac{\left(\frac{n_2}{n_1}I_2\right)^2 R_1}{\text{Short-circuit loss}}$$

Total loss in copper

$$= \text{short-circuit loss} \times (1 + 2\,p\,q\sqrt{1-(P.F.)^2}) \qquad \textbf{(24)}$$

To illustrate this by an example: suppose a transformer has an exciting current of 10 per cent and its short-circuit loss is 2 per cent, what will be the correct copper loss at 80 per cent power factor, supposing that the portion of the short-circuit loss in the primary circuit is 60 per cent of the total value?

Per cent copper loss = per cent short-circuit loss $\times$ (1 + 2 $\times$ 0.1 $\times$ 0.6 $\times$ 0.6) = 2.14 per cent.

The above formula omits the effect of the hysteresis angle, which will slightly increase the correction, but the amount added thereby is too small to be of any importance. It will be noted that at 100 per cent power factor the correction is zero, and since efficiencies are normally figured at this power factor, it will be necessary to make a correction only when efficiencies are required at low power factors.

TABLE I.

SHORT-CIRCUIT LOSS AND IMPEDANCE VOLTS OBTAINED BY METHOD SHOWN IN FIG. 1, WITH VALUES OF IMPRESSED VOLTAGE RANGING FROM ZERO TO NORMAL RATED VALUE, AND WITH POWER FACTORS FROM 99 PER CENT DOWN TO 31 PER CENT. FREQUENCY 60 CYCLES.

Primary volts	Primary amperes	Secondary amperes	Power factor of load	Watts loss	Impedance volts
0	60.0	13.63	30.9	1164.4	276
500	60.2	13.63	30.9	1164.4	277
1000	60.7	13.63	30.9	1164.4	278
1500	60.9	13.63	30.9	1169.4	277
2000	61.3	13.63	30.9	1176.4	278
2500	62.6	13.63	31.6	1176.4	277
2500	58.0	13.63	*32.4	1176.4	276
2500	59.2	13.63	65.6	1189.4	276
2500	61.8	13.63	*69.0	1189.4	279
2500	61.4	13.63	99.2	1189.4	278
2500	59.4	13.63	*99.3	1179.4	277

The differences in the wattmeter measurements given in this table are due to the increase in temperature of the windings during the time the test was in progress. Satisfactory measurements of resistance were not obtained and therefore no correction has been made in the readings.

*In this case the transformer was receiving power at the secondary terminals, instead of at the primary terminals.

(6) Recommendations

In view of the test results given in Section 4 and others that have been obtained from time to time, the authors feel justified in recommending that the old standard method of obtaining short-circuit losses in transformers be retained. In special cases the method described in this paper may be used, but on account of the inconvenience of applying it, its general use is not recommended. It is recommended that the copper loss and regulation be calculated from the short-circuit loss and impedance voltage. The correction to the short-circuit loss to obtain the copper loss

under load may be made according to the practical formula (**24**) which is derived from equation (**21**). The regulation may be figured according to formula (**22**), the correction for the quadrature component given by formula (**23**) being used where required. This well-known formula is based on equation (**17**) and gives very nearly exact values when the correction for the quadrature component is used. It is very much simpler than other less accurate formulas that are in common use.

List of Symbols used in Theoretical Discussion

L_1 = Primary open-circuit inductance
L_2 = Secondary open-circuit inductance
L_0 = Inductance of load
M = Mutual inductance between primary and secondary
R_1 = Primary resistance
R_2 = Secondary resistance
R_0 = Resistance of load
i_1 = Instantaneous value of primary current
i_2 = Instantaneous value of secondary current
e_1 = Primary impressed e.m.f.
$p = 2\pi \times$ frequency
$\check{I}_1$ = Complex variable expression for primary current
$\check{I}_2$ = Complex variable expression for secondary current
$\check{I}_m$ = Complex variable expression for primary open-circuit current
$\check{E}_1$ = Complex variable expression for primary impressed e.m.f.
$\check{E}_2$ = Complex variable expression for secondary normal e.m.f. under load.
$\check{E}_0$ = Complex variable expression for secondary no-load e.m.f.
I_1 = Effective or root-mean-square value of primary current
I_2 = Effective or root-mean-square value of secondary current
I_m = Effective or root-mean-square value of primary open-circuit current
$|I_1|_n |I_2|_n |I_m|_n$ represent the effective value of the nth harmonic of the quantities $\check{I}_1$ $\check{I}_2$ $\check{I}_m$

$\hat{Z}_a$ = For simple sine waves, the effective impedance of the primary circuit under load. For any periodic wave it represents an operation equivalent to impedance on each harmonic of the wave, the value of the impedance changing with each harmonic.

$\hat{Z}_0$ = Similar operation to $\hat{Z}_a$ but representing impedance of load.

$R_a\ L_a$ = Resistance and inductance corresponding to Z_a

$R_b\ L_b$ = Resistance and inductance corresponding to short-circuit impedance.

$R_c\ L_c$ = Resistance and inductance corresponding to impedance of secondary with primary short-circuited.

ϕ_n = Phase angle for nth harmonic.

The symbols used in Section 5 of this paper are defined in the text.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

DETERMINATION OF LOAD LOSS CORRECTION FACTORS FOR ROTATING ELECTRIC MACHINES

BY E. M. OLIN AND S. L. HENDERSON

It is well known that certain of the losses occurring in rotating electric machines can be accurately determined from no-load measurements. Some of the losses, however, cannot be so determined, as, owing to conditions which develop, as load is applied, a gradual increase in these losses takes place.

The difference between the total losses under load and the sum of the separate losses as determined from no-load measurements is commonly known as "load loss" or "stray loss."

This paper will present data relating to the load losses of certain classes of machines and will describe the methods employed to secure the data.

The classes considered are the following:

a. Direct-current motors and generators.

b. Alternating-current generators and synchronous motors.

c. Synchronous converters.

At any given load the only losses occurring in these types which cannot be accurately determined from no-load measurements are the so-called "core loss" and the loss due to eddies set up in the armature conductors by the stray fields of useful currents flowing in these conductors.

In a paper* previously prepared by one of the present writers it was proposed to apply empirical correcting factors to the values of core loss and armature copper loss as determined from no-load measurements in order to arrive at their true values under load.

**Determination of Power Efficiency of Rotating Electric Machines*, E. M. Olin, TRANS. A. I. E. E., 1912, Vol. XXXI, Part II. p. 1695.

Two constants were suggested, the first to be applied to the measured no-load core loss to compensate for the increased loss due to field distortion under load, the second to be applied to the calculated armature I^2r loss to compensate for eddies in the conductors due to the application of load. These eddies include the secondary losses of commutation as well as those set up by useful currents flowing in the conductors.

Since that paper was written, tests have been conducted with a view to establishing the values of these constants. Very early during the progress of these tests it was found that it would not be practicable to separate the increased loss due to load into its two component parts, namely the increase in core loss due to field distortion, and the increase in copper loss due to eddies in armature conductors.

In other words, two separate constants could not be determined, as no satisfactory method could be worked out for arriving at their values. It was found, however, that in each type of machine a fairly uniform ratio exists between the sum of these losses as determined from no-load measurements and their sum as determined from actual load tests.

This relation may be expressed thus: At any given load,

$$\textit{actual core loss} + \textit{actual armature copper loss}$$
$$= \lambda\,(\textit{measured no-load core loss} + \textit{calculated armature } I^2r \textit{ loss}),$$

where λ is a constant depending upon the type of machine and upon the magnitude of the load.

In order to determine the values for this constant, special tests were conducted on each type of machine. In these tests every possible refinement was employed. The most approved methods were used, and the most expert men. All instruments were specially calibrated and great care was used to locate them where they would not be influenced by stray fields. To avoid fluctuations special machines were used to generate the power. Each reading is the average of a series of ten readings taken at intervals of ten seconds. These tests will be referred to throughout as "laboratory" tests to distinguish them from the ordinary commercial tests recorded herein, a large number of which were examined with a view to checking further the values for the constants.

Direct-Current Machines

A convenient way of determining the load losses of direct-current generators or motors is by measuring the power supplied

from outside sources to a pair of coupled machines loaded one against the other by the well-known "pumping back" method. In this test the shafts of two similar machines are rigidly coupled together mechanically, the armatures are connected in parallel electrically and current is made to flow between them by adjusting the field strengths to get the required difference in e.m.f's.

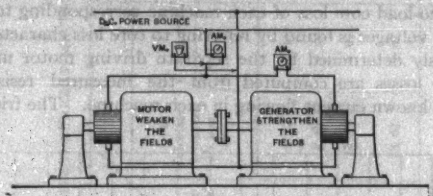


FIG. 1—"LOADING-BACK" TEST OF DIRECT-CURRENT MACHINES—LOSSES SUPPLIED ELECTRICALLY

There are two ways of making the test. In one the losses are supplied by direct electrical connection to the armature circuit of the machines under test, as in Fig. 1; in the other the losses are supplied mechanically by means of a calibrated driving motor, as in Fig. 2.

In either case the power supplied from outside sources rep-

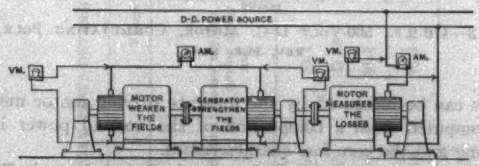


FIG. 2—"LOADING-BACK" TEST OF DIRECT-CURRENT MACHINES—LOSSES SUPPLIED MECHANICALLY

resents the combined losses of the two machines. By a comparison of these losses with the separate losses as calculated from no-load measurements, the increased loss under load due to field distortion and eddies in armature conductors can be determined. If possible, machines exactly alike in characteristics should be used to get the best results.

Referring to Fig. 1, it is to be noted that the machine which

operates as a motor will take a greater armature current than that operating as a generator by the amount of loss current supplied from the outside source. Due allowance must be made for this when computing the separate losses. The internal voltage of each machine is calculated at any load from the known armature current flowing, the resistance of windings and brushes and the known terminal voltage.

The no-load core loss of each machine corresponding to these internal voltages is found by referring to core loss characteristics previously determined by the separate driving motor method. The I^2r losses are computed from the measured resistances and the known current flowing in each machine. The frictional

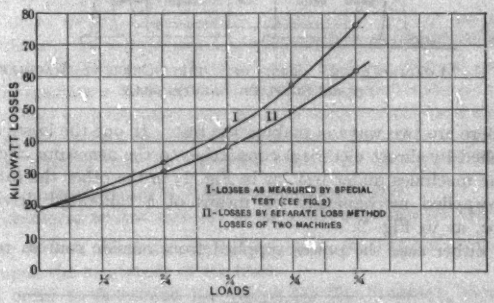


FIG. 3—470-H.P., 500-VOLT D-C. MOTOR, COMMUTATING POLE, 415 REV. PER. MIN.

losses can be measured by the separate driving motor method or computed from a comparison of the no-load power input reading and the core loss characteristics.

When the losses are supplied mechanically, as shown in Fig. 2, the same current circulates in the armature circuit of each machine, but the internal voltages are somewhat different. The separate losses are computed as before.

Laboratory tests were conducted on a pair of 470-h.p. direct-current commutating-pole motors of the most modern design, according to the method described above, with the losses supplied mechanically as shown in Fig. 2. The results of this test are shown in Fig. 3, and in Table I.

In addition to the test described above, the readings taken on

TABLE I

LABORATORY TESTS-DETERMINATION OF CONSTANT λ—DIRECT-CURRENT MACHINES

Values for two machines								Values for one machine	
Machine	Fractional loads	A Losses supplied by driving motor kw.	B Total losses from no-load readings kw.	C Load loss $A - B$ kw.	D No-load core loss kw.	E Calculated armature I^2r loss kw.	λ $\frac{C + D + E}{D + E}$	Efficiencies by separate losses: Without constant λ	Efficiencies by separate losses: With constant λ
470 h.p. motors, 550 volts commutating pole 415 rev. per min. (See Fig. 2) for special test	2/4	33.1	30.96	2.04	13.7	4.22	1.11	91.4	90.9
	3/4	43.15	38.57	4.58	14.0	8.61	1.20	92.3	91.6
	4/4	57.3	49.34	7.96	13.85	15.34	1.27	92.8	91.7
	5/4	76.2	61.44	13.76	13.75	23.43	1.37	92.5	91.1

a pair of 3750-kw. commutating-pole generators which happened to be on the test floor at the same time, were carefully gone over with a view to getting further information as to the values of the constant.

These generators were tested by the "pumping back" method with electrical loss supply, as shown in Fig. 1. Conditions were not as favorable as in the case of the 470-h.p. motors, owing to fluctuations of the power circuit supplying the losses, due partly to the inertia of the heavy rotors. Hence we have not termed this a "laboratory" test. Nevertheless, fairly satisfactory readings were obtained at full load and the value of the correction factor was found to be 1.32.

A number of commercial input-output tests were then examined. Some of these were of motors, with the mechanical output measured by Prony brake. Others were of motor-

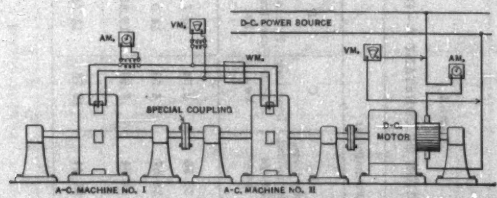


FIG. 4—"LOADING-BACK" TEST OF ALTERNATING-CURRENT MACHINES

generators, where both input and output were measured electrically. The input-output efficiency was in each case checked against the efficiency by separate losses corrected by the factor λ, using values of this constant as found in the tests just described. Table II shows the results of this comparison.

ALTERNATING-CURRENT MACHINES

The load losses of alternating-current generators and synchronous motors may be conveniently arrived at as follows: Two machines made from the same specifications (and therefore of the same wave form) are rigidly connected together and driven from a calibrated motor, as shown in Fig. 4. The rigid connection between the a-c. machines is made by means of a special coupling so arranged that the position of the rotating elements with respect to each other can be varied. There will be certain positions of the rotors when the armature circuits can be paralleled

TABLE II
DIRECT-CURRENT MACHINES—COMMERCIAL TESTS

Machine	Fractional loads	A Core loss at no-load	B Calculated armature I^2r loss	λ as determined by special test	λ (A + B)	Total losses from no-load readings: Without correction factor	Total losses from no-load readings: With correction factor λ	Kilowatts output or input	Efficiency by losses: Without correction factor	Efficiency by losses: With correction factor	Efficiency by input-output
* 30-h.p., 230-volt, 975 rev. per min. d-c. commutating pole motor	2/4	0.433	0.155	1.1	0.646	1.64	1.70	12.97	87.4	86.7	86.3
	3/4	0.428	0.310	1.2	0.885	1.95	2.10	19.06	89.8	89.1	88.2
	4/4	0.418	0.552	1.3	1.26	2.31	2.60	25.08	90.7	89.6	89.2
	5/4	0.405	0.856	1.4	1.74	2.82	3.30	31.12	90.9	89.4	89.8
*35-h.p., 230-volt, 1150 rev. per min. d-c. commutating pole motor	2/4	0.783	0.150	1.1	1.081	2.02	2.07	15.60	87.0	86.2	83.7
	3/4	0.770	0.322	1.2	1.205	2.4	2.55	22.70	89.4	88.5	86.3
	4/4	0.755	0.572	1.3	1.72	2.77	3.16	29.70	90.6	89.3	87.9
	5/4	0.740	0.892	1.4	2.28	3.35	4.00	36.80	91.0	89.3	88.8
*60-h.p., 230-volt, 650 rev. per min. d-c. commutating pole motor	2/4	1.50	0.134	1.1	1.8	3.57	3.74	25.96	86.4	85.6	86.3
	3/4	1.48	0.29	1.2	2.12	3.90	4.25	28.10	89.8	88.9	88.2
	4/4	1.46	0.50	1.3	2.55	4.32	4.91	50.20	91.4	90.1	89.2
	5/4	1.44	0.765	1.4	3.08	5.75	6.63	62.0	92.3	90.8	90.2
†160-kw., 400-volt, 750 rev. per min. d-c. commutating pole generator	4/4	1.98	4.39	1.3	8.28	12.16	14.07	160.0	93.0	92.0	92.3
†260-h.p., 550-volt, 750 rev. per min. d-c. commutating pole motor	4/4	3.25	3.14	1.3	8.30	12.00	13.91	187.0	93.5	92.6	92.8
†175-kw., 550-volt, 600 rev. per min. d-c. commutating pole generator	5/4	8.5	4.11	1.4	17.63	19.71	24.73	219	91.7	90.0	89.5

TABLE II—*Continued.*

Machine	Fractional loads	A Core loss at no-load	B Calculated armature I^2r loss	λ as determined by special test	$\lambda(A+B)$	Total losses from no-load readings: Without correction factor	Total losses from no-load readings: With correction factor λ	Kilowatts output or input	Efficiency by losses: Without correction factor	Efficiency by losses: With correction factor	Efficiency by input-output
†260-h.p., 220-volt, 600 rev. per min. d-c. commutating pole motor	5/4	2.4	9.26	1.4	16.30	21.74	26.38	271.8	92.0	90.3	90.0
200-kw. syn. conv., as direct-current generator, 575-volt, three-phase, 60 cycles, 1200 rev. per min. (See Fig. 12.)	2/5	8.05	0.50	1.09	9.32	15.7	16.5	85.1	84.5	83.9	84.0
	2/4	8.10	0.97	1.10	10.1	16.7	17.7	112.5	87.1	86.4	86.5
	3/4	8.20	1.70	1.20	11.88	17.8	19.8	148.0	89.4	88.3	88.5
	4/4	8.30	2.60	1.30	13.73	19.0	21.8	183.1	90.5	89.3	89.3
	5/4	8.35	3.58	1.30	15.75	20.2	24.0	214.5	91.4	90.0	89.7
*20-h.p., 230-volt, 650 rev. per min. d-c. commutating pole motor	2/4	0.244	0.166	1.1	0.451	1.15	1.19	8.76	86.9	86.3	85.2
	3/4	0.240	0.39	1.2	0.756	1.45	1.58	12.77	88.7	87.7	87.6
	4/4	0.230	0.685	1.3	1.19	1.85	2.03	17.00	89.2	87.5	87.9
	5/4	0.218	1.044	1.4	1.70	2.45	2.89	21.50	88.7	86.2	86.9
*20-h.p., 115-volt, 650 rev. per min. d-c. commutating pole motor	2/4	0.270	0.166	1.1	0.48	1.36	1.40	8.87	84.7	84.1	84.1
	3/4	0.263	0.374	1.2	0.765	1.64	1.77	13.04	87.3	86.5	85.8
	4/4	0.248	0.674	1.3	1.20	2.12	2.40	17.0	87.7	86.2	86.3
	5/4	0.230	1.05	1.4	1.791	2.83	3.34	21.73	87.0	84.8	85.9
*25-h.p., 115-volt, 825 rev. per min. d-c. commutating pole motor	2/4	0.450	0.151	1.1	0.662	1.65	1.71	11.23	85.3	84.6	83.0
	3/4	0.440	0.236	1.2	0.881	2.0	2.18	16.38	87.8	86.9	85.4
	4/4	0.420	0.591	1.3	1.314	2.55	2.85	21.75	88.4	87	85.7
	5/4	0.400	0.956	1.4	1.898	3.23	3.77	27.36	88.3	86.4	85.1
3750-kw., 275-volt, commutating pole d-c. generator 180 rev. per min. (See Fig. 1.)	4/4	50.0	65.8	1.3	150.5	239.9	274.6	3750	94.0	93.2	

* Mechanical output by Prony brake. † Part of motor-generator.

without a flow of cross currents between the machines, in other words, when a condition of synchronism exists. If now the two rotors are shifted slightly with respect to each other, current will tend to flow between the machines, depending in amount on the degree of angular displacement between the rotors.

Any desired load, at practically unity power factor, can be obtained by this method. The power delivered at the shaft of the coupled machines by the calibrated driving motor represents their losses under load conditions.

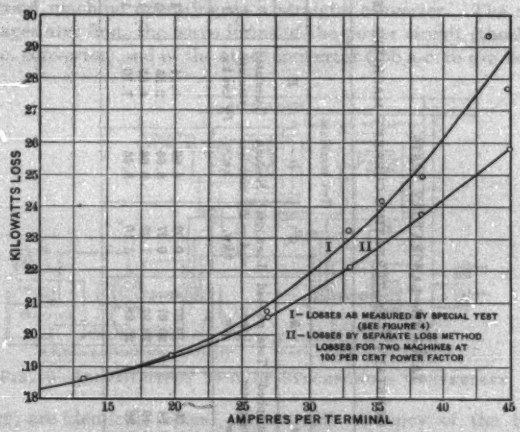


FIG. 5—ALTERNATING-CURRENT GENERATOR, 150 KV-A., 2400 VOLTS, THREE-PHASE, 60 CYCLES, 900 REV. PER. MIN.

By comparing the separate losses as computed from no-load measurements with the losses as shown in the tests described above, the increased loss due to the application of load can be determined.

The machines selected for investigation were two 150-kv-a. 2400-volt 60-cycle belted generators built from the same specifications.

The tests were conducted as described above. (See also Fig. 4.) Laboratory methods were employed. The results are as shown in Table III and Fig. 5.

TABLE III—LABORATORY TESTS

DETERMINATION OF CONSTANT λ—ALTERNATING-CURRENT MACHINES. (SEE FIG. 4)

Machine	Fractional loads	Two machines						One machine	
		A	*B*	*C*	*D*	*E*		Efficiency by losses	
		Losses supplied by driving motor kw.	Total no-load losses kw.	Load loss $= A - B$ kw.	No-load core loss kw.	Calculated armature I^2r loss kw.	λ $\frac{C + D + E}{D + E}$	Without correcting factor	With correcting factor
150 kv-a., three-phase, 2400-volt, 60-cycle a-c. generator	2/4	19.09	19.07	0.02	8.66	1.14	1.002	88.7	88.68
	3/4	20.94	20.67	0.27	8.66	2.55	1.024	91.7	91.6
	4/4	24.19	22.97	1.22	8.66	4.55	1.092	92.9	92.5
	5/4	28.98	25.88	3.10	8.66	7.10	1.197	93.5	92.8

Synchronous Converters

The methods previously described for determining the load losses of direct- and alternating-current motors and generators are not well adapted for synchronous converters. Our experience indicates that the introduction of the necessary boosters in the armature leads complicates the situation to such an extent that the results cannot be relied upon.

For this class of machines the straight input-output method was used, with the following modification. Two identical synchronous converters were used, one operating d-c. to a-c. to feed a second machine operating as a straight converter. The advantages are: first, the wave forms of the power circuit (the d-c. to a-c. converter) and of the other converter (the a-c. to d-c. converter) are identical; second, the ove-rall efficiency of the two synchronous converters can be computed by a comparison of the direct-current input with the direct-current output. This is an advantage, for d-c. measuring instruments are more reliable and give steadier readings than the a-c. instruments. Fig. 6 shows the scheme of connections used for this test.

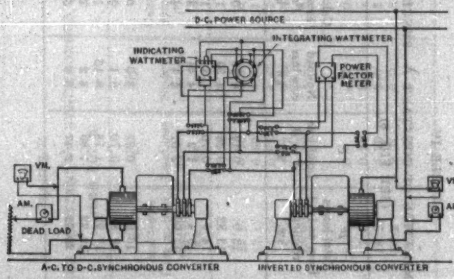


Fig. 6—Input-Output Test of Synchronous Converters

The laboratory tests were made on 60-cycle non-commutating-pole synchronous converters. Two different pairs of synchronous converters were tested and the results are shown in Tables IV and V and in Figs. 7, 8, 9 and 10. At each load, ten readings were taken at ten-sec. intervals and an average taken for each point. It will be seen that the results in the two tests check very well together and go to show that the load loss is small, up to and including full load. On the heavy overloads serious sparking at the brushes occurs and the load loss factor increases rapidly.

TABLE IV

LABORATORY TESTS—DETERMINATION OF CONSTANT λ—SYNCHRONOUS CONVERTERS

(SEE FIG. 6)

Machine	Fractional loads	A Losses from input-output kw.	B Total losses from no-load readings kw.	C Load loss $A - B$ kw.	D No-load core loss kw.	E Calculated armature I^2r loss kw.	λ $\frac{C + D + E}{D + E}$ kw.	Efficiency by separate losses	Efficiency by input-output
200-kw., 625-volt, three-phase, 60 cycles 1200 rev. per min. (See Fig. 6)	2/4	13.19	13.0	0.19	4.36	0.51	1.04	88.5	88.3
	3/4	14.18	13.82	0.36	4.39	1.12	1.07	91.6	91.4
	4/4	15.6	14.9	0.70	4.41	1.99	1.10	93.1	92.9
	5/4	17.6	16.4	1.2	4.44	3.12	1.16	93.8	93.4
	6/4	20.0	17.99	2.01	4.47	4.49	1.22	94.3	93.8
200-kw., 575-volt, three-phase, 60 cycles 1200 rev. per min. (See Fig. 6)	2/4	16.35	16.03	0.32	8.0	0.43	1.04	86.2	85.9
	3/4	17.58	16.8	0.70	8.1	0.95	1.08	90.0	89.6
	4/4	19.22	17.92	1.18	8.15	1.71	1.12	91.8	91.3
	5/4	21.16	19.22	1.89	8.2	2.74	1.17	92.9	92.3
	6/4	23.2	20.73	2.47	8.3	3.84	1.25	92.5	92.8

TABLE V

LABORATORY TESTS—DETERMINATION OF CONSTANT λ—SYNCHRONOUS CONVERTERS—INVERTED

(SEE FIG. 6)

	Fractional loads	*A* Losses from input-output kw.	*B* Total losses from no-load readings kw.	*C* Load loss $A - B$ kw.	*D* No-load core loss kw.	*E* Calculated armature I^2r loss kw.	λ $\frac{C + D + E}{D + E}$	Efficiency by separate losses	Efficiency by input-output
200 kw., 625-volt, three-phase, 60 cycles 1200 rev. per min. (See Fig. 6)	2/4	12.35	12.17	0.18	4.3	0.73	1.04	90.5	90.4
	3/4	13.69	13.17	0.52	4.35	1.44	1.09	92.6	92.3
	4/4	15.5	14.52	0.98	4.42	2.42	1.14	93.8	93.3
	5/4	17.88	16.16	1.72	4.48	3.61	1.21	94.3	93.7
	6/4	20.45	18.00	2.45	4.57	5.05	1.26	94.7	94.0
200 kw., 575-volt three-phase, 60 cycles 1200 rev. per min. (See Fig. 6)	2/4	16.2	15.9	0.3	8.3	0.67	1.03	87.9	87.6
	3/4	17.64	17.0	0.64	8.5	1.30	1.07	90.7	90.3
	4/4	20.0	18.21	1.79	8.6	2.16	1.17	92.3	91.7
	5/4	22.82	20.2	2.62	9.0	3.25	1.21	93.2	92.5
	6/4	25.7	21.85	3.85	9.1	4.39	1.29	93.7	92.6

The results from a number of commercial tests of 60-cycle synchronous converters are shown in Table VI. The efficiencies by input-output in all cases check very closely with those computed from the separate losses, using the correction factor 1.1 at full rated output, the value indicated by the laboratory tests.

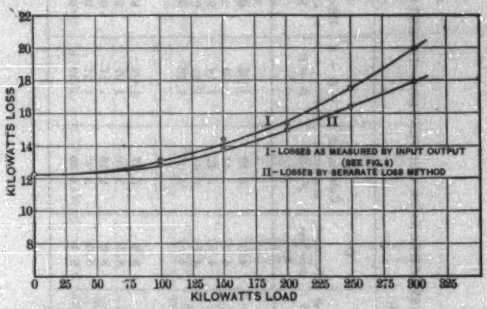


FIG. 7—SYNCHRONOUS CONVERTER, 200 KW., 625 VOLTS, 60 CYCLES, THREE-PHASE, 1200 REV. PER. MIN., NON-COMMUTATING POLE

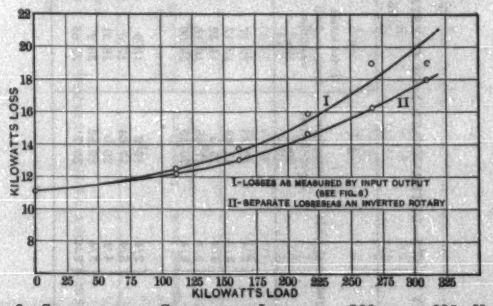


FIG. 8—SYNCHRONOUS CONVERTER INVERTED, 200 KW., 625 VOLTS, 60 CYCLES, THREE-PHASE, 1200 REV. PER. MIN., NON-COMMUTATING POLE

No laboratory tests were made on 25-cycle synchronous converters or on commutating-pole converters of either frequency. Results from a number of commercial tests shown in Table VII seem to indicate, however, that if there is any load loss on 25-cycle converters it is so small that it may be neglected.

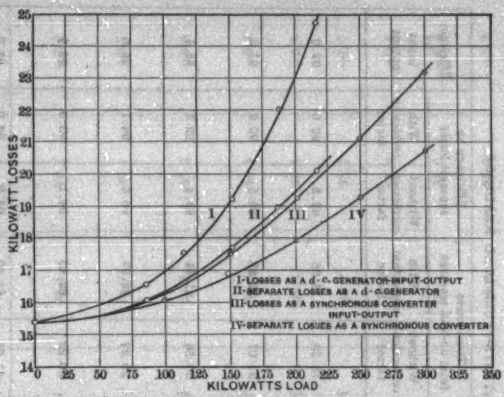


FIG. 9—SYNCHRONOUS CONVERTER, 200 KW., 575 VOLTS, 60 CYCLES, THREE-PHASE, 1200 REV. PER. MIN., NON-COMMUTATING POLE

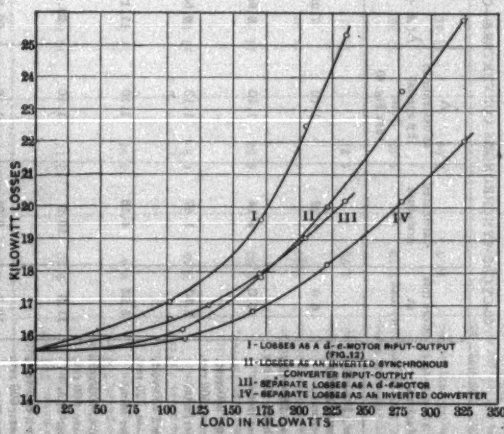


FIG. 10—SYNCHRONOUS CONVERTER INVERTED, 200 KW., 575 VOLTS, 60 CYCLES, THREE-PHASE, 1200 REV. PER. MIN., NON-COMMUTATING POLE

TABLE VI

60-CYCLE SYNCHRONOUS CONVERTERS—COMMERCIAL TESTS—FULL-LOAD READINGS

Machine	Core loss at no-load	Calculated armature I^2r	λ as determined by special test (See Fig. 6)	$\lambda(A+B)$	Kw. output	Total losses from no-load readings		Efficiency by separate losses		Efficiency by input output
						Without correction factor	With correction factor	Without correction factor	With correction factor	
200-kw., 275-volt, three-phase, 1200 rev. per min.	6.0	1.22	1.10	7.95	200.7	16.25	16.98	92.5	92.0	92.0
300-kw., 250-volt, three-phase, 514 rev. per min.	6.0	2.14	1.10	8.95	298.4	21.07	21.88	93.5	93.2	93.3
300-kw., 250-volt, two-phase, 900 rev. per. min.	7.30	1.47	1.10	9.65	299.9	20.56	21.44	93.4	93.3	93.1
500-kw., 250-volt, six-phase, 720 rev. per min.	5.95	4.16	1.10	11.12	504	25.92	26.93	95.0	94.7	94.6
1000-kw., 600-volt, six-phase, 600 rev. per min.	11.3	10.0	1.10	23.42	961	60.28	62.40	94.1	93.9	93.9
1000-kw., 600-volt, six-phase, 600 rev. per min.	10.1	8.21	1.10	20.15	1010	61.66	63.50	94.2	94.0	93.9

TABLE VII

25-CYCLE SYNCHRONOUS CONVERTERS—COMMERCIAL TESTS—FULL-LOAD READINGS

	Core loss at no-load	Calculated armature I^2r loss	Total loss from no-load readings	Kw. output	Efficiency by losses	Efficiency by input-output	Difference in efficiency
200-kw., 600-volt, three-phase, 750 rev. per min.	2.60	2.17	10.16	199.2	95.1	93.1	—2.0
300-kw., 600-volt, three-phase, 750 rev. per min.	2.4	4.92	13.0	293	95.7	96.4	+0.7
300-kw., 650-volt, three-phase, 750 rev. per min.	3.48	4.3	13.46	296.4	95.6	95.2	—0.4
300-kw., 650-volt, three-phase, 750 rev. per min.	3.95	4.59	14.78	319.7	95.6	94.8	—0.8
300-kw., 650-volt, three-phase, 750 rev. per min.	3.70	4.30	14.10	300.3	95.5	96.1	+0.6
300-kw., 650-volt, three-phase, 750 rev. per min.	4.20	4.21	15.11	299.3	95.2	93.5	—1.7
300-kw., 600-volt, three-phase, 750 rev. per min.	3.10	4.42	13.36	295	95.7	96.2	+0.5
500-kw., 600-volt, six-phase, 500 rev. per min.	10.6	2.04	21.43	523	96.1	95.6	—0.5
500-kw., 600-volt, six-phase, 500 rev. per min.	9.0	1.97	18.81	500.8	96.4	97.9	+1.5
500-kw., 600-volt, six-phase, 500 rev. per min.	13.4	2.06	25.37	525.2	95.4	96.5	+1.1
500-kw., 600-volt, six-phase, 500 rev. per min.	8.8	2.04	17.12	498	96.7	95.2	—1.5

TABLE VII—*Continued*

	Core loss at no-load	Calculated armature I^2r loss	Total loss from no-load readings	Kw. output	Efficiency by losses	Efficiency by input-output	Difference in efficiency
500-kw., 600-volt, six-phase, 500 rev. per min.	11.2	2.04	28.1	521.5	95.9	95.0	—0.9
500-kw., 600-volt, six-phase, 500 rev. per min.	8.8	2.04	25.8	538	95.4	94.3	—1.1
500-kw., 1200-volt, three-phase, 750 rev. per min.	5.76	8.1	23.32	499.5	95.5	95.3	—0.2
500-kw., 1200-volt, three-phase, 750 rev. per min.	4.05	8.88	19.81	501.4	96.2	97.0	+0.8
500-kw., 1200-volt, three-phase, 750 rev. per min.	4.90	8.65	22.11	500.6	95.8	96.6	+0.8
500-kw., 1200-volt, three-phase, 750 rev. per min.	4.50	8.95	21.24	499.6	95.9	96.7	+0.8
500-kw., 1200-volt, three-phase, 750 rev. per min.	4.98	8.82	22.76	500.4	95.7	96.5	+0.8
1000-kw., 650-volt, six-phase, 500 rev. per min.	11.50	5.57	36.72	1007	96.5	97.3	+0.8
2000-kw., 600-volt, six-phase, 375 rev. per min.	13.85	18.8	64.6	2008	95.9	98.0	+1.1

*Average difference in efficiency, 0.02.

Readings were taken at different loads on a 25-cycle commutating-pole machine during a temperature test while the meters were swinging somewhat due to variations in the power supply. The results from these readings are plotted in Fig. 11. This curve further indicated that load loss in the case of 25-cycle converters is a negligible quantity and that the efficiency calculated from the separate loss without correcting factors is sufficiently accurate for all commercial purposes.

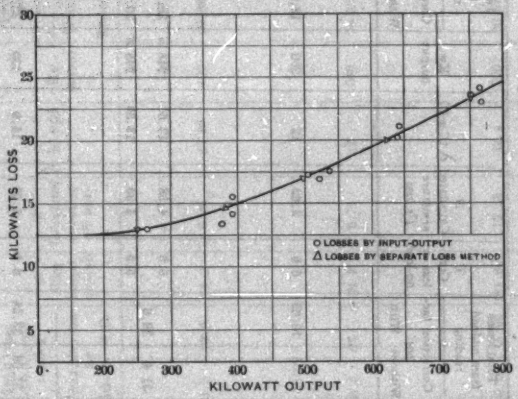


FIG. 11—SYNCHRONOUS CONVERTER, 500 KW., 600 VOLTS, SIX-PHASE, 25 CYCLES, 750 REV. PER. MIN., COMMUTATING POLE—COMMERCIAL TEST

SYNCHRONOUS CONVERTER AS D-C. GENERATOR

In addition to the straight input-output test as described above, a second test was made on the same synchronous converters, operating them as direct-current machines. (See Fig. 12).

The shafts of the two converters were coupled together mechanically and the pair of machines was operated as a d-c. to d-c. motor-generator. A direct comparison of the performance of this type as a synchronous converter and as a d-c. generator was thus obtained. The results are given in Figs. 9 and 10 and show very well the increase in load loss when operating as direct-current machines.

TABLE VIII. MOTOR-GENERATOR SETS—COMMERCIAL TESTS—FULL-LOAD READINGS.

λ for direct-current generator = 1.3 λ for synchronous motor = 1.1

Machine	Synchronous motor						Direct-current generator						Set		
	A Core loss at no-load	*B* Calculated armature I^2r loss	λ $(A+B)$	Kw. input	Total losses from no-load reading: Correction factor Without	Total losses from no-load reading: Correction factor With	*C* Core loss at no-load	*D* Calculated armature I^2r loss	λ $(C+D)$	Kw. output	Total losses no-load readings: Correction factor Without	Total losses no-load readings: Correction factor With	Over-all efficiency by separate losses: Correction factor Without	Over-all efficiency by separate losses: Correction factor With	Efficiency by input-output
200-kw., 250-volt, commutating pole generator 200-h.p., 2200-volt, three-phase, 25-cycle Synchronous motor 750 rev. per min.	3.2	2.6	6.4	23.5	10.03	10.63	5.6	3.62	12	200	18.92	21.70	87.1	86.0	85.1
Three-piece set Two 250-kw., 650-volt, commutating pole d-c. generators 720-h.p., 13,200-volt three-phase, 60-cycle Synchronous motor 720 rev. per min.	15.5	7.9	25.78	570	31.4	33.6	5.6 5.5	4.88 4.95	13.61 13.59	248.5 248.5	20.13 20.10	23.27 23.24	87.4	86.1	87.3
400-kw., 250-volt, commutating pole d-c. generator 580-h.p., 220-volt, three-phase, 30-cycle Synchronous motor 600 rev. per min.	20.2	1.61	24	465.6	31.06	33.24	6.6	5.63	15.9	400	33.16	36.83	86.1	85.1	85.8

TABLE VIII—*Continued.*

Machine	Synchronous motor						Direct-current generator						Set		
	A Core loss at no-load	*B* Calculated armature I^2r loss	λ $(A+B)$	Kw. input	Total losses from no-load reading: Correction factor Without	Total losses from no-load reading: Correction factor With	*C* Core loss at no-load	*D* Calculated armature I^2r loss	λ $(C+D)$	Kw. output	Total losses no-load readings: Correction factor Without	Total losses no-load readings: Correction factor With	Over-all efficiency by separate losses: Correction factor Without	Over-all efficiency by separate losses: Correction factor With	Efficiency by input-output
400-kw., 600-volt, commutating pole d-c. generator 560-h.p., 2200-volt three-phase, 60-cycle Synchronous motor 720 rev. per min.	9.0	4.2	14.52	453	21.3	22.6	4.0	6.06	13.08	400	23.86	26.88	89.8	88.9	88.3
1000-kw., 275-volt, commutating pole d-c. generator 1440-h.p., 5500-volt, two-phase, 60-cycle Synchronous motor 514 rev. per min.	36.0	8.6	49.1	1159	66.5	71	24.9	9.71	45	1000	74.51	84.9	87.7	86.6	86.3
1000-kw., 550-volt commutating pole d-c. generator 1440-h.p., 2200-volt, two-phase, 60-cycle Synchronous motor 514 rev. per min.	16.7	11.05	30.5	1124	46.26	48.96	11.60	13.35	32.4	1000	62.27	69.75	90.2	89.4	88.9

TABLE VIII—*Continued.*

Synchronous motor							Direct-current generator						Set		
Machine	*A* Core loss at no-load	*B* Calculated armature I^2r loss	$\lambda(A+B)$	Kw. input	Total losses from no-load reading: Correction factor Without	Total losses from no-load reading: Correction factor With	*C* Core loss at no-load	*D* Calculated armature I^2r loss	$\lambda(C+D)$	Kw. output	Total losses no-load readings: Correction factor Without	Total losses no-load readings: Correction factor With	Over-all efficiency by separate losses: Correction factor Without	Over-all efficiency by separate losses: Correction factor With	Efficiency by input-output
1000-kw., 600-volt, commutating pole d-c. generator 1440-h.p., 4600-volt, two-phase, 60-cycle Synchronous motor 514 rev. per min.	18.0	7.85	28.45	1143	50.11	52.7	32.2	11.3	56.5	1000	82 47	95.51	88.3	87.2	87.5
125 PER CENT LOAD READINGS λ—direct-current generator = 1.4 λ—synchronous motors = 1.2															
400-kw., 600-volt, commutating pole d-c. generator 580-h.p., 2200-volt, three-phase, 60-cycle Synchronous motor 720 rev. per min.	8.9	6.1	18	561	25.25	28.25	4.1	8.8	18.07	500	27.45	32.6	90.5	89.2	89.1
240-kw., 500-volt, commutating pole d-c. generator 370-h.p., 370-volt, three-phase, 60-cycle 1200 rev. per min.	5.2	4.3	11.4	342	14.8	16.7	4.6	7.05	16.3	300	22.8	27.5	88.9	87.1	87.8
150-kw., 250-volt, commutating pole d-c. generator 225-h.p., 440-volt, three-phase, 60-cycle 900 rev. per min.	8.3	2.8	13.32	226.5	15.0	17.22	6.2	4.4	14.86	187.5	19.1	23.35	84.6	82.2	82.7

Motor-Generator Sets

A number of motor-generator sets were examined and the constants determined from the laboratory tests were applied to the sum of the no-load core losses and calculated armature copper losses of each machine. The over-all efficiency of the set from the corrected losses was then calculated and compared with the over-all efficiency from the input-output readings taken during commercial tests. The results are shown in Table VIII.

While an examination of these results shows some discrepancies, it must be remembered that the input-output tests are merely of the commercial variety and are probably as nearly correct as average tests of that description.

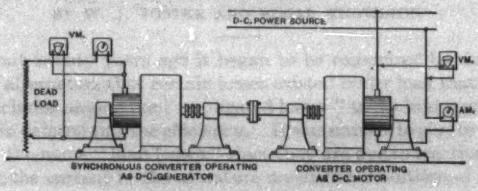


Fig. 12—Input-Output Test of Synchronous Converters as Direct-Current Machines

Recommendations

As a result of our investigation we suggest the use of correction factors for computing from the separate losses, the efficiencies of the rotating electric machines discussed in this paper, namely—a-c. generators, synchronous motors, d-c. generators, d-c. motors, and synchronous converters. The said correction factors to be applied to the sum of the no-load core loss and the armature I^2r loss, as calculated from no-load measurements of resistance. We submit the following values as being approximately correct for well-designed apparatus of the types mentioned:

Fractional loads	Value of constant			
	2/4	3/4	4/4	5/4
Direct-current generator Direct-current motor	1.1	1.2	1.3	1.4
Alternating-current generator Synchronous motor } *Stranded conductors	1.01	1.03	1.10	1.2
†60-cycle synchronous converter	1.04	1.07	1.10	1.2
All 25-cycle synchronous converters	1	1	1	1

* Does not apply to machines with deep strap conductors, in which the eddy current loss in the copper may be large.

† Non-commutating-pole type. Tests on commutating-pole type not completed.

These values apply only to well-designed machines, as shown by moderate losses, low temperatures and satisfactory behavior at the commutator.

In the case of machines having undue temperature elevations or those showing faulty commutation, the load losses may be of considerable magnitude and the above constants will not hold good. Such machines should be investigated individually, according to the method described herein, if the true efficiency is to be determined.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

LOAD LOSSES OF ALTERNATING-CURRENT GENERATORS

BY W. J. FOSTER AND EDGAR KNOWLTON

About twenty years ago it began to be recognized by designers of alternators that certain losses existed under load that were not included among the "segregated losses" taken into consideration in determining the efficiency. It was natural to give to these losses the name "load losses," since they are due to reactions set up by the current in the armature under the conditions of load, and cannot be reproduced on open circuit or calculated directly from measured current and resistance, as can the I^2R of armature and field. The current in the armature corresponding to that of any load could be easily established by simply short-circuiting the armature terminals and introducing the proper exciting current into the field winding. Hence, for the lack of something more accurate, it became customary to measure the losses on short circuit in the same manner as core losses were determined, and take these as indicative of the losses that would exist under actual load. Obviously, the reactions on short circuit are exaggerated, hence, it has been considered fair to take a fraction of the short-circuit losses as the load losses. The present A. I. E. E. rule, Section 117, specifies one-third as the proper amount.

The method of determining the efficiency by the "segregated losses" method is undoubtedly deficient in at least two particulars.

1. The determination of core losses at the normal potential (corrected though it may be for internal resistance and reactance) can be considered as only an approximation of that existing under the influence of armature reaction when the flux is distorted and of varying density across the magnetic circuit.

2. No satisfactory method has yet been evolved of measuring the eddy currents that may be produced directly by the current in the armature under the load conditions.

However, it may be said that any alternator that has high load losses under normal load conditions, will have high losses under short circuit. Another good criterion of the design in the matter of load losses is the static impedance test with field removed, using wattmeters to measure the energy input.

That load conditions affect the hysteresis losses, becomes very apparent when we consider the case of an unbalanced condition of load between the phases or the exaggerated condition of single-phase load, where the pulsating m.m.f. produces a flux of double frequency, thereby introducing losses in parts of the magnetic circuit which are free from losses in the open-circuit condition of uniform flux. That load conditions have a tendency to increase eddy current losses has been shown by the high temperatures of many alternators in actual service, where the temperature increments are greater than they should be if only what may be called legitimate losses existed. In some cases temperatures have produced charring of insulation and rapid deterioration where the heating, due to the I^2r alone, should be conservative, and where the determination of segregated losses, and possibly heat runs on open circuit under what was taken to be equivalent heating, gave no indication of trouble from excessive temperatures.

Load losses may be defined as all losses due to the presence of current in the armature windings in excess of the following:

Open-circuit core loss at rated $+Ir$ potential.

I^2r of armature and field due to the actual resistance of the circuits.

The load losses may be regarded as made up of two components; the necessary or legitimate, and the illegitimate. The first of these is small and hardly worth considering in its effect on the efficiency. The second may be so large as to materially lower the efficiency and seriously impair the life of the machine. On the other hand, the second component may be appreciable, and one to be reckoned with in determining the efficiency, and yet be desirable to introduce into the design. For instance, a solid is often preferable to a sectionalized conductor, since the additional eddy current loss may be compensated for by greater net cross-section. Even though this compensation be partial, no greater heating may result, due to the better transfer of heat to

the surface, and the use of the solid conductor is justified by the cheaper construction, greater mechanical strength and ease of repairs.

Determination of Load Losses

In a well-designed machine the magnitude of the load losses is so small compared with the capacity that it is impracticable to determine it by direct measurement of input. This has been shown by numerous trials.

A method has been proposed for machines of the enclosed type where the greater part of the losses are removed by the air passing through the machine. This consists in measuring the volume and temperature rise of the air and estimating the losses from the specific heat of the air. In this method there are the following sources of error. The percentages of error given apply to the ordinary commercial test:

Transfer of heat to the room through the frame (amount unknown).

Difference in the specific heat of air due to the presence of moisture (inappreciable).

Measurement of the volume of air (at least 5 per cent error).

Determining the average temperature of the ingoing and outgoing air (at least 5 per cent error).

With these errors it is evident that load losses of considerable magnitude would remain undiscovered.

A modification which eliminates most of the errors is to run the machine at some no-load condition in which the losses can be easily determined; also run the machine under load. The difference in the temperature rises of the air under the two conditions represents a certain loss which can be calculated from the no-load results. The load losses may then easily be estimated. By making such a test carefully, any abnormal load losses should be detected. The authors, however, have had no opportunity to make a trial of this method.

To obtain more satisfactory results there has been devised a number of other methods based on the following plan:

The alternator is run in such a manner that all magnetic and current densities and all reactions shall be the same as under load and the energy measured be only that due to the losses. The excess of the losses thus determined over that obtained by the usual segregated loss method will represent the true load losses. Several tests of this nature have been made with more than usual care, for the purposes of this paper. A general description of the tests follows and a comparison of the results is given in Table III.

Segregated Loss Method

The A. I. E. E. method of determining the total losses consists in obtaining the various losses under partial load conditions and taking their sum as the total loss, making certain allowances for the load losses. The following A. I. E. E. rules relate to the losses:

102 Bearing Friction and Windage. The magnitude of bearing friction and windage (which may be considered as independent of the load) is conveniently measured by driving the machine from an independent motor, the output of which may be suitably determined.

106 Core Losses. In machines these losses should be determined on open circuit and at a voltage equal to the rated voltage $+Ir$ in a generator, and $-Ir$ in a motor, where I denotes the current strength and r denotes the internal resistance of the machine. They should be measured at the correct speed and voltage, since they do not usually vary in any definite proportion to the speed or to the voltage.

107 Note. The total losses in bearing friction and windage, brush friction, magnetic friction and eddy currents can, in general, be determined by a single measurement by driving the machine with the field excited, either as a motor, or by means of an independent motor.

108 Retardation Method. The no-load iron, friction, and windage losses may be segregated by the Retardation Method, in which the generator should be brought up to full speed (or, if possible, to about 10 per cent above full speed) as a motor, and, after cutting off the driving power and excitation, frequent readings should be taken of speed and time, as the machine slows down, from which a speed-time curve can be plotted. A second curve should be taken in the same manner, but with full field excitation; from the second curve the iron losses may be found by subtracting the losses found in the first curve.

109 The speed-time curves can be plotted automatically by belting a small separately excited generator (say 1/10 kw.) to the generator shaft and connecting it to a recording voltmeter. When the retardation method is not feasible, the frictional losses in bearings and in windage, which ought, by definition, to be included in determining the efficiency, may be excluded; but this should be expressly stated.

110 Armature-Resistance Loss. This loss may be expressed by $p\,I^2r$: where r resistance of one armature circuit or branch, $I =$ the current in each armature circuit or branch, and $p =$ the number of armature circuits or branches.

114 Load Losses. The load losses may be considered as the difference between the total losses under load and the sum of the losses above specified.

116 Estimation of Load Losses. While the load losses cannot well be determined individually, they may be considerable and, therefore, their joint influence should be determined by observation. This can be done by operating the machine on short circuit and at full load current, that is, by determining what may be called the "short-circuit core loss." With the low field intensity and great lag of current existing in this case, the load losses are usually greatly exaggerated.

117 One-third of the short-circuit core loss may, as an approximation, and in the absence of more accurate information, be assumed as the load loss.

In order to have a comparison of the value of the short-circuit core loss and the other armature losses, there have been prepared Tables I and II on 25- and 60-cycle generators, respectively. The accuracy of the individual determinations may be questioned, but they are given, as it is probable that the average of all the values is approximately correct. The data on horizontal lines

TABLE I.

OPEN-CIRCUIT, SHORT-CIRCUIT, AND I^2r LOSSES OF 25-CYCLE ALTERNATING-CURRENT TWO- AND THREE-PHASE GENERATORS.

	1	2	3	4	5	6	7
			Losses in per cent of kv-a.				
			Core loss				
	Kv-a.	Volts	Open cir.	Short cir.	½ of s.c.	I^2r arm.	Total 3 + 5 + 6
1	270	2300	1.74	0.00	0.00	2.08	3.82
2	360	2300	3.17	0.29	0.1	0.90	4.17
3	937	2300	0.95	0.24	0.08	0.95	1.98
4	937	3300	1.47	0.71	0.24	1.04	2.75
5	937	6600	1.05	0.60	0.20	0.94	2.19
6	1111	220	2.07	1.46	0.49	0.68	3.22
7	360	13200	2.39	0.88	0.29	1.16	3.84
8	1667	2300	1.88	0.80	0.27	0.70	2.85
9	1667	6600	1.07	0.49	0.16	0.50	1.73
10	2222	2300	1.21	0.79	0.26	0.83	2.30
11	2342	480	1.40	1.00	0.33	0.80	2.53
12	430	480	1.56	0.71	0.24	1.67	3.50
13	420	240	2.05	1.01	0.34	3.08	5.47
14	1270	9000	1.33	0.54	0.18	0.82	2.33
15	840	480	1.58	0.59	0.20	1.70	3.48
16	720	480	1.64	0.81	0 27	2 09	4.00
17	1800	2300	2.11	0.29	0.1	1.24	3.45
18	9000	6600	1.00	0.28	0.09	0.44	1.53
Average	1516	3416	1.65	0.64	0.21	1.2	3.06

No. of machines above the average short-circuit core loss, 9.
No. of machines below the average short-circuit core loss, 9.

3, 4, 5, 6, 8, 9, 10, and 11 in Table I, and 2, 3, 4, 5, 6, 7, 8, 9, 11, 14, 15, 16, 19, 20, 29, 33, 36, 39, 40, 42 and 43 in Table II, are on steam turbo-generators and the core losses were taken by the retardation method with turbine wheels assembled; consequently the results are not especially accurate. The core losses on the other machines were taken by driving with a direct-current motor and are more reliable.

TABLE II. OPEN-CIRCUIT, SHORT-CIRCUIT, AND I^2r LOSSES OF 60-CYCLE ALTERNATING-CURRENT TWO- AND THREE-PHASE GENERATORS.

	1	2	3	4	5	6	7
			Losses in per cent of kv-a.				
			Core losses				
	Kv-a.	Volts	Open cir.	Short cir.	½ of s.c.	I^2r arm.	Total 3+5+6
1	318	2300	1.41	0.52	0.17	1.18	2.76
2	625	2300	1.59	0.71	0.24	1.10	2.93
3	1875	2300	1.38	1.68	0.56	0.38	2.22
4	937	600	1.60	0.96	0.32	0.66	2.58
5	937	2300	1.45	1.18	0.06	0.44	2.28
6	420	2300	1.37	0.18	0.06	1.10	2.56
7	1250	2300	1.55	0.90	0.30	0.92	2.77
8	1563	480	1.31	0.83	0.28	0.69	2.28
9	1563	2300	1.31	0.83	0.28	0.51	2.10
10	480	600	1.63	1.06	0.35	1.19	3.17
11	2000	2300	1.04	0.29	0.10	0.62	1.76
12	635	2300	1.48	0.43	0.14	1.06	2.68
13	793	2300	1.51	0.72	0.24	0.55	2.33
14	2500	480	1.30	0.25	0.08	0.40	1.78
15	2500	2300	1.82	0.43	0.14	0.41	2.37
16	2500	6600	1.85	0.09	0.03	0.33	2.21
17	600	600	1.98	0.50	0.17	1.18	3.33
18	600	480	2.63	1.32	0.44	1.34	4.41
19	3125	2300	1.63	0.99	0.33	0.40	2.36
20	3125	2300	1.66	0.34	0.11	0.35	2.12
21	635	4150	1.99	0.64	0.21	1.18	3.38
22	480	11000	2.53	0.26	0.09	1.65	4.27
23	370	600	1.49	0.22	0.07	1.52	3.08
24	720	600	2.87	1.15	0.38	0.94	4.19
25	600	11000	2.53	0.25	0.08	1.47	4.08
26	540	220	2.28	0.95	0.32	1.27	3.87
27	1920	2300	1.61	1.32	0.44	0.54	2.59
28	720	600	1.54	0.25	0.08	1.15	2.77
29	6250	4000	0.96	0.43	0.14	0.31	1.41
30	1275	11000	1.51	0.74	0.25	1.00	2.75
31	1200	10000	2.73	0.38	0.13	0.98	3.84
32	1440	2300	1.83	1.25	0.42	0.73	2.98
33	8333	2200	1.05	0.53	0.18	0.31	1.54
34	1200	2300	1.50	0.49	0.16	1.34	3.02
35	6000	2300	0.91	0.51	0.17	0.53	1.61
36	9000	4600	1.00	0.13	0.04	0.30	1.34
37	3000	2300	1.33	0.47	0.16	0.75	2.26
38	12000	6600	1.18	0.24	0.08	0.32	1.58
39	14000	4600	0.87	0.05	0.02	0.31	1.20
40	14000	6000	1.45	0.09	0.03	0.24	1.72
41	15000	4150	0.70	0.48	0.16	0.36	1.22
42	15000	7000	0.91	0.15	0.05	0.25	1.21
43	15000	11431	1.45	0.34	0.11	0.20	1.76
44	7800	4000	1.28	0.55	0.18	0.50	1.96
45	9800	6900	1.58	0.72	0.24	0.40	2.22
46	12000	6600	1.72	0.20	0.07	0.32	2.11
47	6600	4000	1.89	0.43	0.14	0.53	2.56
Average	4111	3670	1.58	0.58	0.19	0.72	2.49

Number of machines above the average short-circuit core loss, 18.
Number of machines below the average short-circuit core loss, 29.

A description of Tables I and II follows:

Column 1. Kv-a. rating. This is on the "continuous" or "single rating" basis, which is being considered in the present revision of rules.

" 2. Potential.

" 3. Open-circuit core loss at rated $+ I r$ volts (in per cent of kv-a. rating).

" 4. Short-circuit core loss at rated current (in per cent of kv-a. rating.

" 5. One-third of the values in column 4.

" 6. Calculated $I^2 r$ loss of armature at rated current in per cent of the kv-a. rating.

" 7. Total of columns 3, 5, and 6.

In addition to the data given in Tables I and II there were a few accurate tests made, the results of which are included in Table III.

Modified Segregated Loss Method

This method differs from the segregated loss method in that the reactive drop of the armature current is taken into account. The core loss is taken at a voltage corresponding to rated volts plus $I R$ drop plus $I X$ drop. The $I X$ drop is determined as follows:

Let A = Ampere-turns field to pass full-load current through the armature when it is short-circuited.

R = ampere-turns of armature reaction.

ϕ = angle of lag between volts and current.

X = $I X$ drop which is the volts from the no-load saturation curve corresponding to $A - R$.

V = rated volts.

V_m = volts at which the core loss is taken.

$V_m = \sqrt{V^2 + X^2 + 2 V X \sin \phi}$

See Table III for results of tests.

Phase Characteristic Method

This method of testing consists in running an alternating-current generator as a synchronous motor without mechanical load at rated voltage and current. The energy input is taken for the above conditions of voltage and current with field under- and over-excited. From the average of these two quantities there is subtracted the $I^2 r$ of the armature winding and the energy input at unity power factor and rated voltage.

See Table III for results of tests.

Circulating Energy Method

This test consists in coupling two alternators mechanically and electrically, and belting a direct-current motor to the combination to supply the losses. The angle of the two rotors is shifted by means of slots in the coupling so that rated current will flow with rated volts at unity power factor.

The losses of the two machines are determined by the input from the driving motor.

See Table III for the results of tests.

TABLE III.
RESULTS OF CAREFUL TESTS BY SEVERAL DIFFERENT METHODS OF DETERMINING LOAD LOSSES. 60-CYCLE ALTERNATORS.

	1	2	3	4	5	6	7
				Losses in per cent kv-a.			
	Phase	kv-a.	Rev. per min.	Seg.	Mod. seg.	Phase char.	Circ. energy
1	3	860	720				
2	Excess loss				0.035		
3	½ short circ. core loss			0.151	0.151		
4	Total load losses			0.151	0.186	0.302	0.49
5	1	600	720				
6	Excess loss				0.025		
7	½ short circ. core loss			1.300	1.300		
8	Total load losses			1.300	1.325		3.82
9	3	300	600				
10	Excess loss				0.063		
11	½ short circ. core loss			0.099	0.099		
12	Total load losses			0.099	0.162	0.150	0.29
13	3	110	900				
14	Excess loss				0.055		
15	½ short cir. core loss negligible						
16	Total load losses				0.055		0.359

Description of Table III

Column 1. Number of phases.
" 2. Capacity in kv-a.
" 3. Revolutions per minute.
" 4. Losses in per cent of kv-a. by the segregated method. Note that all losses are in actual per cent. For instance the loss for line 3 in this column is 1.3 kw.
" 5. Losses by modified segregated method.
" 6. Losses by phase characteristic method.
" 7. Losses by the circulating energy method.

Line 1. Rating of the alternator.

" 2. Excess core losses. The open-circuit core loss at

" (rated $+ Ir + Ix$, potential) $-$ the open-circuit core loss at (rated $+ Ir$, potential).

" 3. One-third of short-circuit core loss.

" 4. Total load losses as determined by the various methods.

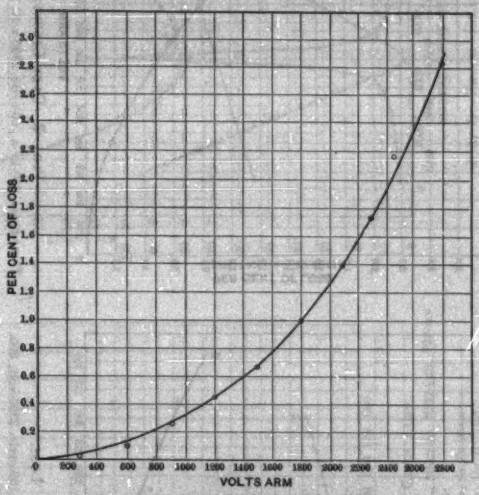


FIG. 1—OPEN-CIRCUIT CORE LOSS.
Three-phase, 300-kv-a., 60-cycle, 2300-volt, 600-rev. per min. generator.

Lines 5 to 8 inclusive: These give the same relative data as lines 1 to 4 inclusive; the difference being that lines 1 to 4 refer to three-phase, and 5 to 8 to single-phase operations of the same generator.

Lines 9 to 12 inclusive: These give the same relative data on a 300-kv-a. alternator as lines 1 to 4 inclusive.

Lines 13 to 16 inclusive: These give the same relative data on a 110-kv-a. alternator as lines 1 to 4 inclusive.

As a matter of interest there have been included Figs. 1 to 11 inclusive, which relate to the characteristics of the machine tested.

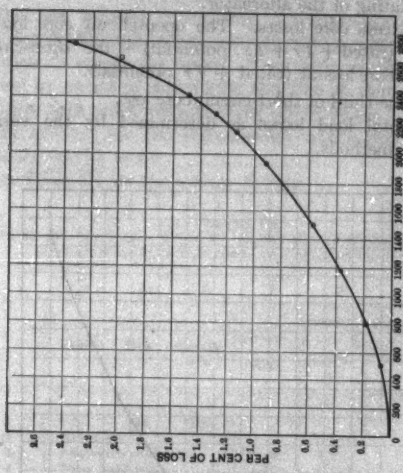


FIG. 3—OPEN-CIRCUIT CORE LOSS.

Three-phase, 860-kv-a., 60-cycle, 2300-volt, 720-rev. per min. generator.

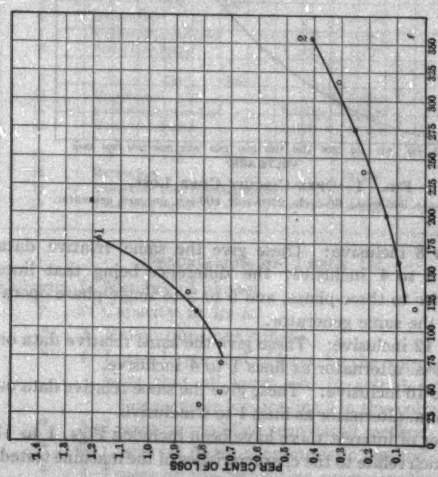


FIG. 2—SHORT-CIRCUIT CORE LOSS.

Three-phase, 300-kv-a., single-phase, 150-kv-a., 60-cycle, 2300-volt, 600-rev. per min. generator

Curve 1—Short-circuit core loss, single-phase.

Curve 2—Short-circuit core loss, three-phase.

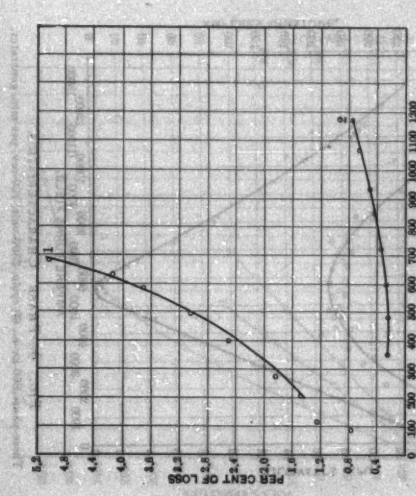


FIG. 4—SHORT-CIRCUIT CORE LOSS.

Three-phase, 860-kv-a., single-phase, 600-kv-a., 60-cycle, 2300-volt, 720-rev. per min. generator

Curve 1—Short-circuit core loss, single-phase.
Curve 2—Short-circuit core loss, three-phase.

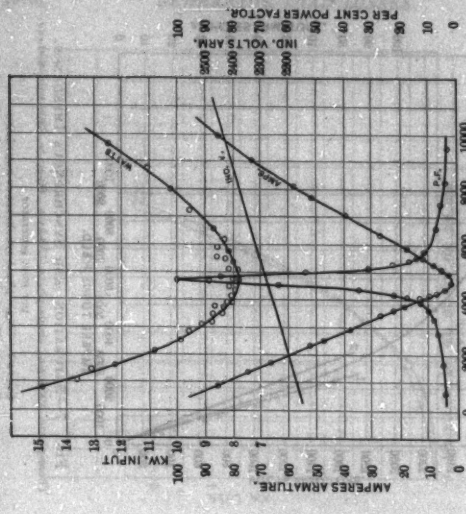


FIG. 5—PHASE CHARACTERISTICS.

Three-phase, 300-kv-a., 60-cycle, 2300-volt, 600-rev. per min. generator.

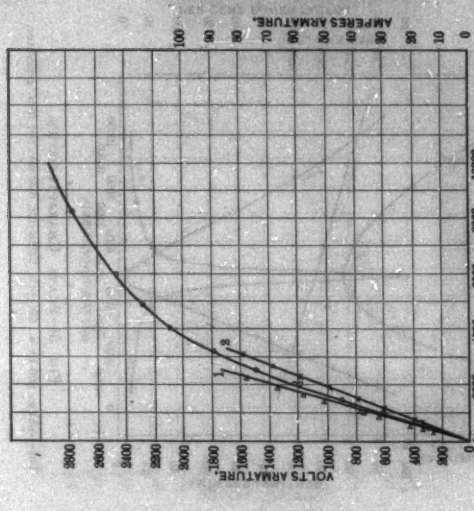


FIG. 7—SATURATION AND SYNCHRONOUS IMPEDANCE.
Three-phase, 330-kv-a., single-phase, 150-kv-a., 60-cycle, 2300-volt, 600-rev. per min. generator
Curve 1—Single-phase synchronous impedance
Curve 2—Three-phase "

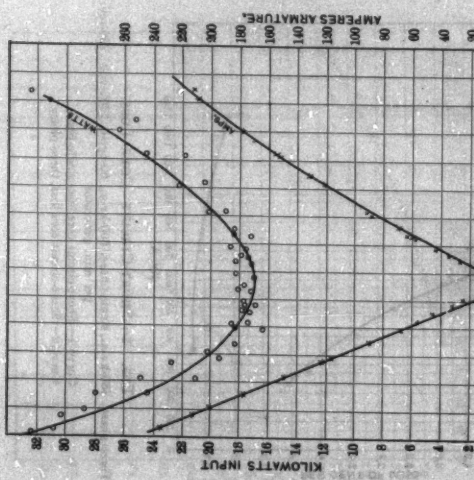


FIG. 6—PHASE CHARACTERISTICS.
Three-phase, 860-kv-a., 60 cycle, 2300-volt, 720-rev. per min. generator.

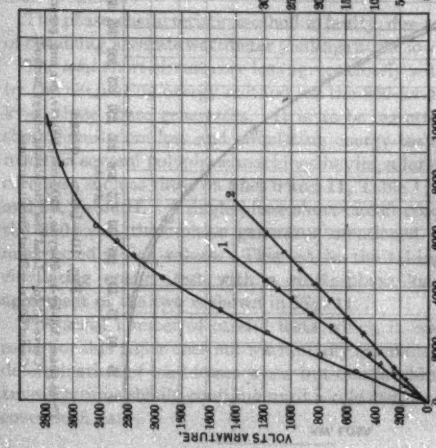


FIG. 8—SATURATION AND SYNCHRONOUS IMPEDANCE.
Three-phase, 860-kv-a., single-phase, 600-kv-a., 60-cycle, 2300-volt, 720-rev. per min. generator
Curve 1—Single-phase synchronous impedance
Curve 2—Three-phase " "

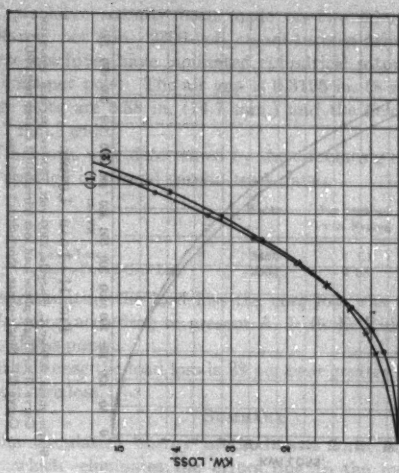


FIG. 9—LOAD LOSSES.
Three-phase, 860-kv-a., 60-cycle, 2300-volt, 720-rev. per min. generator
Curve (1) (0)—Load loss (circulating energy method).
Curve (2) (x)—Short-circuit core loss

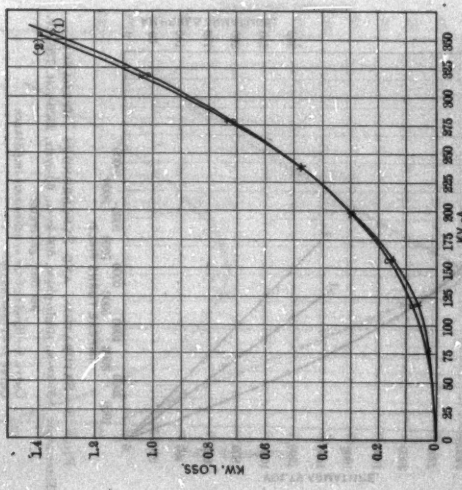


FIG. 10—LOAD LOSSES.

Three-phase, 300-kv.-a., 60-cycle, 2300-volt, 600-rev. per min. generator
Curve (1) (o)—Load loss (circulating energy method).
Curve (2) (x)—Short-circuit core loss.

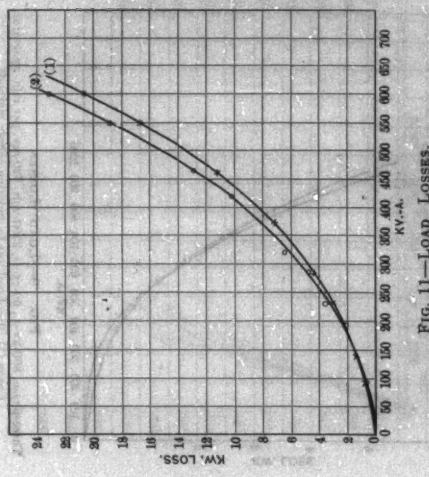


FIG. 11—LOAD LOSSES.

Single-phase, 600-kv.-a., 60-cycle, 2300-volt, 720-rev. per min. generator.
Curve (1)—Single-phase load loss (circulating energy method).
Curve (2)—Single-phase, short-circuit core loss.

Tests have recently been made on two 60-cycle, 300-kv-a. 3600-rev. per min., 2300-volt steam-turbine-driven generators. These machines have laminated cylindrical rotors, wound with six coils per pole. The air gap is 0.3125 in. (8 mm.), the armature slots are 0.58 in. (14.7 mm.) and the field slots 0.50 in. (12.7 mm.) wide.

The losses were determined by the circulating energy method. An average of several careful tests gave:

	Watts	Per cent of kv-a. Rating
Load Loss	3450	1.15
Short-Circuit Core Loss	2500	0.83

In estimating the load loss the core loss was taken at rated $+ Ir$ volts, according to present A. I. E. E. Rule 106, on page 506 of this paper.

In this case the load loss is 38 per cent greater than the short-circuit core loss.

Summary

The circulating energy method is a form of input-output test which eliminates the errors due to the measurement of energy equal to the capacity of the machine. When two duplicate machines are available, the authors consider it the best of the four methods.

The phase characteristic method is faulty, due to the difficulty of obtaining accurate wattmeter readings at the low power factors.

The *total* short-circuit core loss agrees closely with the load loss by the circulating energy method for the 860-kv-a. and the 300-kv-a. three-phase generators. It is to be regretted that careful short-circuit core loss and circulating energy tests could not be made on several polyphase machines having a large short-circuit core loss, such as those on lines 6 and 11, Table I; and lines 3, 5, and 27, Table II. A single-phase short-circuit core loss taken on the 860-kv-a. three-phase generator mentioned above, showed unexpectedly high values. This led to the taking of a careful circulating energy test with a single-phase load. The close agreement of the two is shown in Fig. 11.

The small number of careful tests which it was possible to make for this paper does not warrant any recommendation for the determination of load losses when but one machine is available. Investigations should continue until a rule can be established to cover such cases.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

NOTES ON STRAY LOSSES IN SYNCHRONOUS MACHINES

BY F. K. BRAINARD

Since the Institute rule of determining "load loss," which may more properly be called stray loss, seems in error, an analysis of short-circuit tests of synchronous machines was made with the idea of determining, if possible, the nature of this loss and so the probable relationship between stray loss with actual load on the machine, and the measured loss on short-circuit which cannot be accounted for by armature I^2R.

These losses are probably due almost entirely to the following causes:

a. Eddy current loss in the armature conductors, or rather extra loss due to the unequal distribution of current in the conductor. See *Eddy Currents in Large Slot-Wound Conductors*, A. B. Field, TRANSACTIONS A. I. E. E., 1905, XXIV, p. 761.

b. Eddy current and hysteresis loss due to flux from the armature coils getting into parts of the machine not intended to carry magnetic flux, such as coil supports, end shields, etc.

c. Extra eddy current and hysteresis loss due to the change in distribution of flux in the magnetic circuit.

The eddy current factor for each machine was computed according to Field and the tests were plotted upon logarithmic paper to determine the law of variation of short-circuit loss with armature current.

In the case of slow or moderate-speed machines it was found that the loss varied practically as the square of the armature current and that the stray loss unaccounted for by cause (a) mentioned above was small and usually negligible. The loss due to cause (b) will be small in this case on account of the

relatively short ends of the coils. Hence it would appear that the stray loss due to cause (c) in low-speed machines is negligible or can practically be eliminated by proper construction of armature cores.

In the case of high-speed turbo-alternators the loss unaccounted for by eddy currents in the conductors is large, and short-circuit tests made with and without end shields indicate that cause (b) previously mentioned is mainly responsible. In one case removal of the end shields reduced the loss on short-circuit 28 per cent. Hence it would seem that even in this case there is very little stray loss in the core of a well-built machine.

For any synchronous machine the loss due to the "Field effect" is probably practically the same on load as on short-circuit for the same armature current. The same undoubtedly applies to the loss due to flux from the armature coils getting into the unlaminated parts of the machine. However, the loss due to change in distribution of the magnetic flux is probably considerably greater on short-circuit than with the same armature current at full voltage; but since this part of the stray loss can probably be reduced to a negligible amount by proper design and workmanship, it would seem that the Institute rule should be modified to make stray loss equal to, say, one half of the difference between the measured short-circuit loss and the calculated I^2R loss, instead of one third of this difference as at present.

Then the total losses in any synchronous machine would be determined as follows:

1. Core loss, windage and friction, determined by driving the machine with a separate motor at normal speed and normal voltage with the armature open-circuited. This to be assumed constant at all loads.

2. Armature resistance loss and stray loss, determined by driving the machine at normal speed with the armature short-circuited and with sufficient excitation to cause full-load armature current to flow. Of course the power required to drive the machine unexcited should be deducted so as not to include windage and friction twice.

3. Field excitation loss to be calculated from the field resistance hot, the amperes excitation being determined from the regulation curves.

It has been suggested that in the case of turbo-alternators there is an additional loss under load which does not appear on either open-circuit or short-circuit, due to the increased leakage flux

from the field resulting from the greater exciting current. However, no attempt has been made, to the writer's knowledge, to measure this loss, but the probable existence of it should serve as an additional argument for taking more than one third of the "short-circuit core loss" as stray loss.

The following table gives the results of a number of short-circuit tests on various machines. The column headed "n" is the exponent in the equation kw. $= aI^n$ obtained by plotting upon logarithmic paper, where kw. = total loss on short-circuit, I = armature current and a and n are constants.

Rating of generator					Calculated armature copper* loss at full load	Measured short-circuit loss with full load current	n	Short-circuit loss Calc. I^2R	Eddy current constant
Kv-a.	Volts	Phases	Cycles	Rev. per min.					
2100	2300	3	25	107	22.4	25.7	2.16	1.15	1.29
1000	2300	3	25	94	17	19	1.86	1.12	1.12
250	1100	2	60	120	5.8	5.7	2.15	0.98	1.00
250	480	3	60	120	8.2	8.2	1.95	1	1.03
375	600	3	60	120	9.9	10.5	2.07	1.06	1.00
600	240	3	25	125	8.1	11.7	2	1.44	1.30
600	2300	3	60	150	7.6	9.2	2.07	1.21	1.19
300	4150	3	60	600	3.1	4.2	1.61	1.35	1.00
300	4150	3	60	600	3.1	3.1	1.95	1	1.00
400	7500	3	30	150	9.9	9.5	1.99	0.96	1.00

* The calculated copper loss is based upon 50 deg. cent. coil temperature. As the temperature of the stator coils was not read during the short-circuit tests, a part of the lack of agreement between the calculated and measured short-circuit loss is undoubtedly due to this.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

STRAY LOSS IN DIRECT-CURRENT COMMUTATING MACHINES

BY H. F. T. ERBEN AND H. S. PAGE

During the past two years there has been considerable discussion on the subject of load loss and many misunderstandings have arisen as to its nature and magnitude. To one not familiar with the accepted definition of the term, load loss might imply all of the losses occurring in a machine other than the no-load losses. In order to designate more clearly the subject under discussion the term defined in Section 114 of the Standardization Rules of the A. I. E. E. will be referred to in this paper as "stray loss" instead of "load loss."

In direct-current commutating machines, stray loss may be divided into two elements: first, "commutation loss," consisting of such losses as arise from the improper reversal of current in the coils undergoing commutation, and second, "loss due to flux distortion," resulting from the action of armature flux on main field flux.

Perfect commutation demands that the current in the coils be reversed in such a manner that it falls from a positive maximum to zero, and continuing, risesto a negative maximum uniformly as successive segments pass under the brush, and the magnitude of commutation loss depends upon the extent of divergence from this ideal condition. This latter condition is only obtained in cases where the coils undergoing commutation are passing through such a flux that an e.m.f. is generated in them whose instantaneous values are always equal to and opposite in direction to their own self-induction. Such a condition is most closely obtained in the modern commutating-pole machines and in consequence the so-called commutation loss can be neglected. In

machines of the non-commutating pole type, where it is most difficult to obtain the correct commutating flux, it is obvious that commutation loss may be of considerable magnitude, as frequently the current is not properly reversed during commutation. Even if the correct commutating flux is obtained for a a given load on such a machine it does not vary in such proportion to the current as to be correct for other loads. Non-commutating pole machines will, therefore, have one element of the stray loss which is at a maximum at some fixed load but which will increase very rapidly at different loads.

A fair example of flux distortion is shown in Fig. 1. The symmetrical curve shown in solid line represents the flux distribution at no-load as obtained by the oscillograph. The corresponding broken line curve shows flux distribution at full load. It will be seen readily that with the iron worked through an entirely dif-

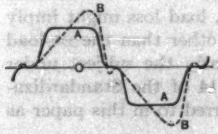


FIG. 1

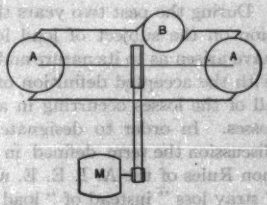


FIG. 2

ferent cycle at full-load than at no-load the hysteresis and eddy current losses will be altered. The maximum flux density in the teeth at no-load represented by $O\ A$ is raised 30 per cent to 40 per cent as represented by $O\ B$, thereby increasing the hysteresis loss and causing additional leakage through the slots with a resultant increase in eddy current loss in the copper.

In order to make efficiency tests taking stray losses into account it is necessary to load the machine to its full capacity, carefully observing either the input and output, or, if two duplicate machines are at hand, the total losses may be observed directly by the following method. In Fig. 2 the machines under test have the fields separately excited. At zero load no power is supplied from B, and M supplies power for all the losses except excitation. As load is applied, B furnishes power to circulate the armature current, the counter e.m.f. of machines A-A being kept alike, and M supplies additional power to compensate for the stray loss,

thus allowing both machines to be fully loaded. Instruments indicating the losses are entirely independent of those measuring the load, consequently losses can be observed with a minimum error.

This paper will present data showing the magnitude of stray loss occurring in various types of "direct-current machines" and "synchronous converters," and from these data it will probably be possible to derive approximately correct formulas for general use in determining this loss. From facts later presented it will be seen that the actual value is such that quite an error in its estimation is permissible.

Input-output tests for efficiency are very expensive and frequently give inconsistent results. Errors of observation directly affect the determination of efficiency by this method, and as an example of the possibilities of error the following table is given, showing results on 37 motors tested by the brake method.

H.p. output		H.p. stray loss	H.p. output		H.p. stray loss	
2.01	+	0.0080	20.5	—	0.0615	
2.03	—	0.0264	20.5	—	0.1025	
3.1	—	0.0403	2.00	+	0.084	
3.1	+	0.034	1.99	+	0.0139	
2.99	+	0.0508	3.05	+	0.0061	
3.00	—	0.117	2.95	—	0.0678	
4.97	+	0.0249	4.92	—	0.0541	
4.93	+	0.045	4.84	—	0.0921	
4.94	+	0.1475	7.67	+	0.0077	
4.95	+	0.0638	7.4	—	0.126	
7.7	—	0.0231	10.06	—	0.040	
7.72	—	0.0077	9.82	—	0.167	
7.4	+	0.0074	14.96	—	0.06	
7.4	+	0.0444	15.12	+	0.0605	
10.08	+	0.0201	20.05	+	0.0802	
10.23	+	0.113				
9.62	—	0.279	Total 311.75		3.6689	Total +
9.62	—	0.192			1.8047	Total —
14.9	+	0.313				
15	—	0.166			1.8642	Net total +
15.15	+	0.273				= 0.6 %
15.07	—	0.181				

The resultant efficiencies were compared with efficiency figures obtained by the segregated loss method and the difference in each case considered as stray loss. The instruments were calibrated just before tests were made and all observations carefully checked. Many of the stray loss values appear as negative, and in spite of the care taken to have correct observations made, the results indicate a probable error greater than the stray loss itself. In these thirty-seven motors, ranging in capac-

ity from 2 h.p. to 20 h.p., the total net stray loss shown was 1.86 h.p. for a total capacity of 312 h.p., giving a stray loss of 0.6 per cent. Inconsistencies which appear in these figures show that the results are of value only as an indication of the average stray loss and cannot be taken as correct for any one machine. This table is not given as an example of the most accurate results obtainable but rather as an example of results which will be obtained unless what might be termed "laboratory methods" are resorted to.

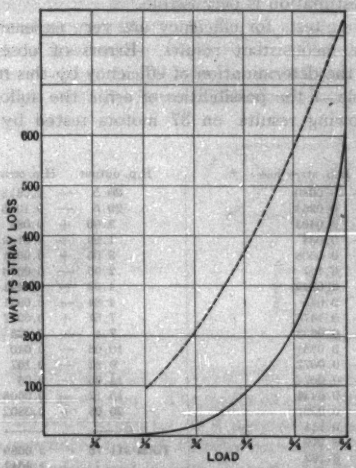


FIG. 3—FOUR-POLE, 20-KW., 1000-REV. PER MIN. GENERATOR.
I^2R armature 1060 watts. Iron and eddy current loss 360 watts

Stray loss values on five machines tested by the method described in connection with Fig. 2 are shown in Figs. 3 to 8 inclusive. In these tests the utmost care was taken in every detail, the losses were observed directly and the results are much more reliable than tabulated results given for the 37 small motors. The 150-kw. and 400-kw. generators, also the 500-kw. converter, were not fitted with commutating poles, consequently they show a stray loss at no-load due to the initial brush shift.

I^2R loss in the armature copper and iron plus eddy current loss as determined at no-load are given in each case.

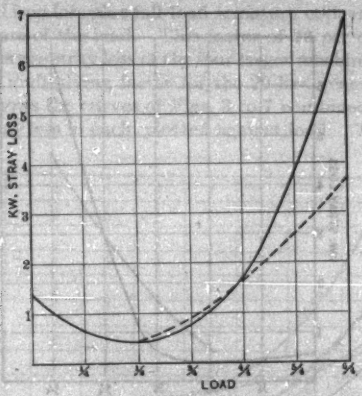


FIG. 4—SIX-POLE, 150-KW., 225-REV. PER MIN. GENERATOR.
I^2R armature 4700 watts. Iron and eddy current loss 1600 watts

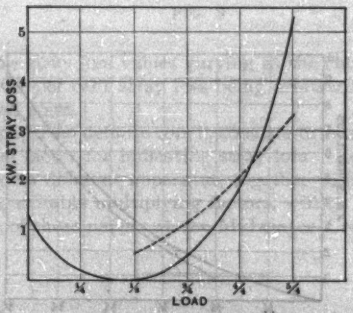


FIG. 5—FOUR-POLE, 500-KW., 750-REV. PER MIN., SYNCHRONOUS CONVERTER RUN AS 300-KW. GENERATOR.
I^2R armature, 3750 watts. Iron and eddy current loss 4400 watts.

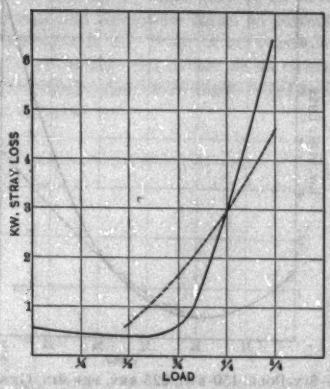


FIG. 6—EIGHT-POLE, 400-KW., 240-REV. PER MIN. GENERATOR
I^2R armature 7680 watts. Iron and eddy current loss 3720 watts

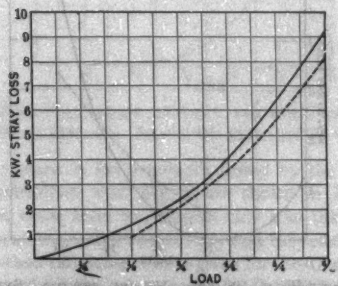


FIG. 7—FOUR-POLE, 500-KW., 720-REV. PER MIN. GENERATOR
I^2R armature 6400 watts. Iron and eddy current loss 7400 watts

Dotted curves shown in Figs. 3 to 8 are based on the assumption that stray losses at normal load are equal to 26 per cent of the no-load iron loss plus full-load armature copper loss and vary as the square of the load. This factor of 26 per cent, chosen to suit the average stray loss of the four larger machines, is evidently too high a multiplying factor for the 20-kw. generator.

Fig. 8 shows the curves of Figs. 3 to 7 combined with the percentage stray loss in each, plotted against load. The two dotted

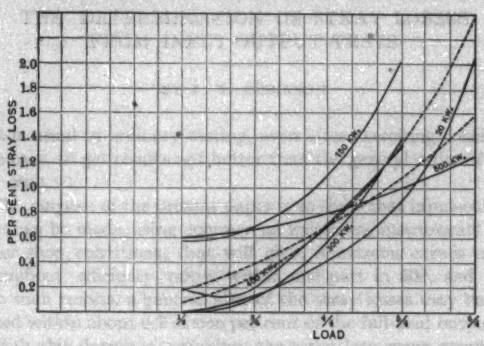
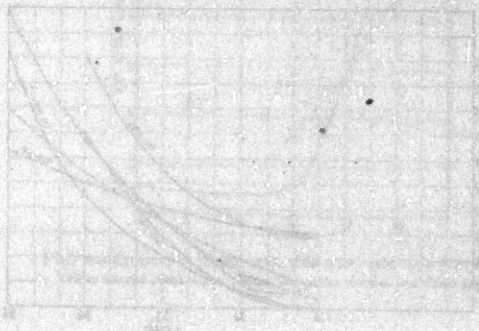


FIG. 8

curves show stray loss values varying as the cube and square of the load, 0.7 per cent stray loss being arbitrarily chosen at the normal load point.

In this paper no definite conclusions are drawn as to a suitable multiplying factor for indicating stray loss. Results of further tests made on different apparatus, together with a recommendation as to suitable multiplying factors, will be presented in the discussion of these papers at the Midwinter Convention of the Institute.



A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

THE DETERMINATION OF STRAY LOSSES FROM INPUT-OUTPUT TESTS

BY L. T. ROBINSON

It is usual in ordinary testing, even after exercising considerable care, to get results not better than the general order of one per cent.

The purpose of the present paper is to show that input-output tests can be made, using commercial measuring instruments and under shop conditions, that will give, if extreme care is taken throughout, efficiency values within one part in 500, and that with such results, a general idea of the stray losses may be obtained within about 0.2 of one per cent of the full-load output.

With this degree of precision, the stray loss curve expressed as per cent of full-load output, and plotted against the output of the machine, can be shown as a curved belt, 0.4 per cent wide, thus giving the stray losses definitely to a varying degree of approximation depending on the amount of such loss.

In computing stray losses from efficiency tests by input-output method, the fact that some of the points obtained do not lie within the prescribed belt is felt to be due more to the fact that certain components of the losses which are determined under no-load are variable than to any failure of the efficiency determinations to come within the prescribed limits. For example, in one instance, Curve 3, Table XIV, the brush and bearing friction alone would, if varied about 25 per cent in the right direction, reduce the stray losses to zero, and it is felt that some such effect caused the losses on 100 and 125 per cent load on this set to fall below what would ordinarily be expected.

If this point had been more fully appreciated during the progress of the tests, certain components of the no-load losses

that enter largely into the final results would have been determined at frequent intervals during the tests, instead of once for all before the efficiency runs. Careful examination of the final tests shows that the difficulty is not so much to be found in obtaining a trustworthy measure of the efficiency as in obtaining the true stray losses, by substracting from the definitely known total losses, under load, the somewhat indefinitely known no-load components corresponding to each full-load determination.

In the examples chosen, the stray losses do not exceed the general order of 1 per cent of the full-load output, and hence the stray losses, assuming that the no-load losses remain constant, may be definitely known within 20 per cent. Obviously, the approximation will be 10 per cent if the stray losses are 2 per cent of full-load output, and 40 per cent if the stray losses are $\frac{1}{2}$ per cent of full-load output.

The accuracy obtainable in this way is, of course, decidedly inferior to that obtainable if the losses could be obtained by direct measurement, using only ordinary care in obtaining the results. However, direct methods are not always known for determining stray loss which may be applied to any and all types and sizes of machines to which input-output testing is applicable, and the development and acceptance of any such methods must depend, in the final analysis, on some over-all efficiency measurement by input-output tests or by similar means.

If it has been shown that the attainable precision is of the general order of 1 in 500, the presumption is that directly determined stray losses falling within the belt would represent more definitely the magnitude of the losses sought, than the center of the belt, and also more correctly the change in such losses with change of load. On the other hand, it is always possible to omit from consideration some conditions of testing when stray losses are directly determined, and determination of over-all efficiency within 0.2 per cent precludes the possibility of large stray losses, or any that would be of interest to the user, being overlooked.

Besides the degree of precision possible in obtaining the efficiency in terms of the test instruments employed, must be considered the calibration and testing of the instruments used, so that the input and output may be known in the same terms.

In all the cases considered, the input was alternating current, and the voltage and current components were of such magnitude that current and pressure transformers were required in the measurements. The output was direct current.

In estimating the permissible average deviation in results the following were considered:

1. Determination of input and output in terms of the instrument employed.
2. Precision of wattmeters used for input.
3. Precision of instrument transformers used.
4. Resistance of shunts used for output in connection with millivoltmeters.
5. Precision of millivoltmeters used with shunts for measuring output current.
6. Voltmeters for measuring pressure of d-c. output.

No attempt will be made to give in conventional style a complete discussion of the probable error in relation to the six things involved, or to establish the correctness of the conclusions reached, except by reference to the tabulated results or to the curves which follow. The contention is that the results obtained usually indicate that the precision estimated is more often attained than not. All the points determined from averages are given, and enough of them lie outside the estimated belt to indicate, as would be expected, that not every point will fall within the probable region.

Taking up the various headings in order:

1. The efficiency, or ratio of instrument readings, output divided by input, was determined in connection with each complete observation, and the deviation of each efficiency or ratio so computed from the average, was used as a basis for determining the average deviation as follows:

$$\text{Average deviation of mean} = \frac{\Sigma d_1 \ldots d_n}{R\, n \sqrt{n}}$$

where $d_1 \ldots$, and $d_n \ldots$, are the individual variations from the average ratio, n is the number of observations taken and R is the ratio of input to output. The number of observations is increased until the average deviation is about 0.15 per cent.

In determining average deviation of mean it is preferable to follow the procedure of Tables V to XV and use the ratio of input reading to output reading, rather than to complete each separate efficiency. The labor is much less and the opportunity is entirely removed to be unconciously influenced by preconceived notions of what efficiency may be expected.

2. Wattmeters were checked by comparison with usual standards at several points very close to the respective values to be

determined, and these checks were compared carefully with previous similar sets of observations to determine with greater accuracy the true values to be used. The average deviation of these values at any point did not exceed 0.07 per cent.

3. Instrument transformers used were checked by potentiometer methods of comparison giving average deviation of 0.05 per cent for current and the same for pressure transformers.

4. Resistance of shunts used for measuring the d-c. output was not considered in connection with the precision estimates. It is possible, either by a single determination using a great deal of care, or by averaging a number of independent determinations, to know the resistance of these shunts within limits so small that they would not appreciably affect the accuracy of the results.

5. Millivoltmeters used on these shunts for measuring d-c. were felt to be somewhat more capable of accurate comparison with standards than the wattmeters, therefore the value 0.05 per cent was taken.

6. Voltmeter errors were estimated to be the same as millivoltmeter, 0.05 per cent.

Effects of temperature variation were eliminated by carrying out all the tests to completion when the series was started, and disturbing influences of surrounding machinery and circuits were very carefully guarded against. In addition to this, shielded instruments were used in every instance.

In must be borne in mind quite clearly that no attempt is being made to state that instruments can be ordinarily relied upon, based on the usual single comparison, to within anything like the accuracies here estimated. It is usual to take only one reading at a point, instead of a closely bunched set of three or five readings, and to neglect entirely previous comparisons at the same point made on the instrument. The average deviation in connection with all the items referred to was handled in the same way as that given under (1).

For a final precision measure we get

$$\sqrt{0.15^2 + 0.07^2 + 0.05^2 + 0.05^2 + 0.05^2 + 0.05^2} = 0.19 \text{ per cent}$$

or roughly, as previously stated, 0.2 per cent. The only significance that was attached to this very elementary computation, was to draw from it the conclusion that, by using very unusual care in all the work, the desired degree of precision could be obtained, and it is believed that the results amply justify this conclusion. This estimate refers to efficiency alone, and, for reasons pre-

viously given, cannot be extended, in all cases, to cover the stray loss determinations as well.

It is usually customary to translate values obtained in a manner similar to those referred to above into "probable error" by multiplying by about two-thirds, but this was not done, in order to be on the safe side.

Conclusions

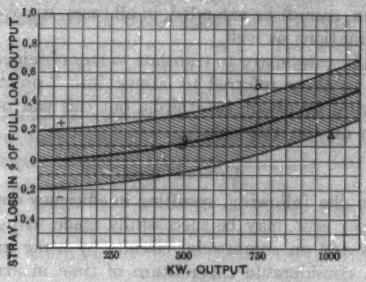
Tests like the following, resulting in efficiency determination within 0.2 per cent, may be successfully made with commercial instruments and on commercial circuits by using unusual care and with a considerable expenditure of time in arranging the tests and taking the observations. The labor of tabulating and computing the results, together with the labor in connection with the checking of instruments and accessories, is far more than the labor of obtaining the observations or setting up the tests.

In the checking of the instruments and computing the test results, a high order of skill and reliability is demanded, such as can be obtained only by training average operators to do the work with the necessary degree of care by keeping them continuously employed at it for some time, or as an alternative, utilizing several high-priced men for computing and arranging for such tests. In either case the cost of the work, if it is done well enough to be of value, will be so great that it is not permissible except in connection with large sets of comparatively high cost and as a check method for demonstrating the reliability of other methods better suited to commercial needs. The method, is, therefore, clearly one that can be considered only in connection with special investigations.

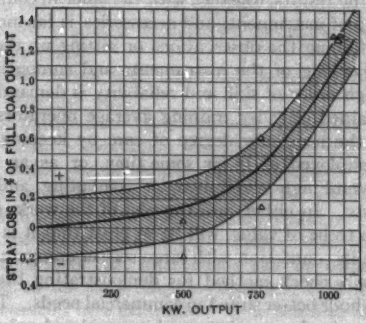
The test observers need not be especially skilled if computation of deviations from average are carried on simultaneously with the test and the number of separate observations increased until the desired precision limits are obtained. Such unskilled observers may increase the number of readings necessary from 9 or 10 per point to three or four times that number, or even more, with the corresponding increase in labor of computing, etc.

The same effect may occur with unsteady current supply.

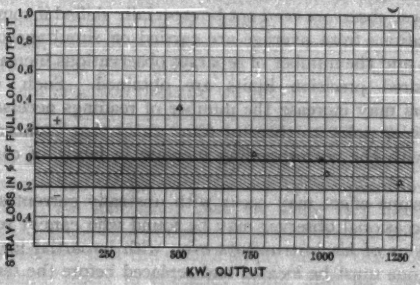
An occasional observer may be found who cannot record the indications of his instruments even with impartial inexactness. Such a one must be located and replaced before the test can be satisfactorily concluded.



CURVE 1



CURVE 2



CURVE 3

Reference to Curve 1 will show that redeterminations at 50 per cent load made on succeeding days checked very closely because presumably the conditions of bearing and commutator did not differ. This is also shown on Curve 2, at 100 per cent load.

These points are referred to simply to emphasize the fact that the load loss values could, as stated, be brought closely within the belts, if the losses determinable at no-load and which vary within relatively wide limits from time to time, had been ascertained at the same time that the efficiency point was taken.

TABLE I

THREE-UNIT SET—1135-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO TWO 500-KW., 125-VOLT DIRECT-CURRENT GENERATORS

50 per cent load	Obs. No.	Kw. Input	Kw. Output	Per cent efficiency	Deviation from mean
	1	614.2	502	81.8	1.1
	2	583.3	486.8	83.5	0.6
	3	562.4	464	82.6	0.3
	4	599.8	497	83.1	0.2
	5	598.2	496	83	0.1
	6	590.8	494.3	83.7	0.8
	7	584.7	490.5	83.8	0.9
	8	602.3	493.5	82	0.9
	9	588.8	489.5	83.1	0.2
	10	602.6	495.5	82.3	0.6
Average		592.71	490.91	82.9	$\frac{0.57}{\sqrt{10 \times 82.9}} = \pm 0.22\ \%$

Test output		Seg. loss		Seg. loss input	
490.91	+	100.8	=	591.71	$\frac{490.91}{591.71} = 83\%$ seg. loss eff.

Test input		Seg. loss input		Stray loss
592.71	—	591.71	=	+ 1.0 kw. = +0.10% of normal load output.

TABLE II

THREE-UNIT SET—1135-KV-A., 6600-VOLT SYNCHRONOUS MOTOR DIRECT CONNECTED TO TWO 500-KW., 125-VOLT, DIRECT-CURRENT GENERATORS

50 per cent load	Obs. No.	Kw. Input	Kw. Output	Per cent eff.	Deviation from mean
	1	589.3	470.5	80	2.8*
	2	611.3	508	83.2	0.1
	3	597	494.5	83	0.1
	4	605.6	505	83.5	0.4
	5	612.2	512	83.8	0.7
	6	599.8	495.7	82.6	0.5
	7	604.4	499	82.7	0.4
	8	602.4	499	83	0.1
	9	598.4	498.5	83.2	0.1
	10	611.4	507	82.9	0.2
Average	(without 1)	604.72	502.07	82.8	$\frac{0.3}{\sqrt{9} \times 82.8} = \pm 0.12\%$

Test output		Seg. loss		Seg. loss input	
502.07	+	101.2	=	603.27	$\frac{502.07}{603.27} = 83.2\%$ seg. loss eff.

Test input		Seg. loss input		Stray loss
604.72	—	603.27	=	+1.45 kw. = +0.145% of normal load output

* Values in these tables marked with an asterisk rejected on account of being over three times greater than the average.

TABLE III

THREE-UNIT SET—1135-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO TWO 500-KW., 125-VOLT, DIRECT-CURRENT GENERATORS

75 per cent load	Obs. No.	Kw. Input	Kw. Output	Per cent eff.	Deviation from mean
	1	879.92	766.5	87.1	1.1
	2	881.8	760	86.2	0.2
	3	942.9	728	77.3	8.2*
	4	892.8	770.3	86.4	0.4
	5	881.9	760.9	86.3	0.3
	6	896.8	766.1	85.4	0.6
	7	896.8	771.1	85.9	0.1
	8	877.4	758.8	86.5	0.5
	9	873.8	752.8	86.2	0.2
	10	891.3	762.3	85.6	0.4
	11	912.1	781	85.6	0.4
	12	879.9	750.4	86.5	0.5
	13	896.8	766.3	85.4	0.6
	14	875.7	744.8	85.1	0.9
	15	853.5	742.4	87	1
Average	(without 3)	885.03	761	86.05	$\frac{0.5}{\sqrt{14} \times 86.05} = \pm 0.15\%$

Test output		Seg. loss		Seg. loss input	
761	+	119	=	880	$\frac{761}{880} = 86.5\%$ seg. loss eff.

Test input		Seg. loss input		Stray loss
885.03	—	880	=	+ 5.03 kw. = +0.503 % of normal load output

TABLE IV

THREE-UNIT SET—1135-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR DIRECT CONNECTED TO TWO 500-KW., 125-VOLT, DIRECT-CURRENT GENERATORS.

Full load	Obs.	Kw. Input	Kw. Output	Per cent eff.	Deviation from mean
	1	1140	1003	87.8	0.2
	2	1120	1000	89.5	1.9
	3	1157	1003	86.7	0.9
	4	1196	1009	84.2	3.6*
	5	1142	993	87	0.6
	6	1172	1009	86	1.6
	7	1156	1016	87.5	0.1
	8	1142	1000	87.5	0.1
	9	1138	1028	90.5	2.7*
	10	1138	1035	90.9	3.1*
	11	1167	1041	89.2	1.6
	12	1156	1018	88	0.4
	13	1146	1003	87.5	0.1
	14	1169	1022	87.5	0.1
	15	1145	996	87.1	0.5
	16	1161	1016	90.6	2.8*
	17	1120	987	88.2	0.6
	18	1128	984	87.2	0.4
	19	1195	1029	6	1.6
	20	1157	1014	87.6	0.0
	21	1117	993	89	1.4
	22	1120	986	88.7	1.1
	23	1160	1022	88.3	0.7
	24	1139	1012	88.9	1.3
	25	1142	1012	87.6	0.0
	26	1198	1025	85.6	2
	27	1169	1019	87.2	0.4
	28	1140	1003	88	0.4
	29	1150	1009	87.6	0.0
	30	1157	1016	87.8	0.2
	31	1142	1004	87.9	0.3
	32	1145	1006	87.8	0.2
	33	1161	1001	86.5	1.1
Average	(without 4, 9, 10, 16)	1150	1007.8	87.6	$\frac{0.69}{\sqrt{29} \times 87.6} = \pm 0.14\ \%$

Test output		Seg. loss		Seg. loss input	
1007.8	+	140.5	=	1148.3	$\frac{1007.8}{1148.3} = 87.76\%$ seg. loss eff.

Test input		Seg. loss input		Stray loss
1150	—	1148.3	=	+1.7 kw. = +0.17% of normal load output.

Brush and bearing friction including windage = 23.98 kw.

TABLE V

TWO-UNIT SET—1120-KV-A., 6600-VOLT SYNCHRONOUS MOTOR CONNECTED TO A 1000-KW., 250-VOLT, DIRECT-CURRENT GENERATOR

50 PER CENT LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Deviation from mean
1	342.8	10600	30.91	0.213
2	339.8	10420	30.72	0.023
3	340.8	10450	30.65	0.047
4	339.3	10390	30.61	0.087
5	339.3	10380	30.60	0.097
6	338.8	10350	30.58	0.117
7	343.8	10610	30.92	0.223
8	344.8	10530	30.59	0.107
Average	341.2	10466	30.69	$\frac{0.1146}{\sqrt{8}\times 30.69} = \pm 0.132\%$

Ratio of trans. 1789.4

Mult. fact. of shunts 48.6

Kw. 610.1 508 $\frac{508}{610.1} = 83.3\%$ eff. input-output.

Test output Seg. loss Seg. loss input

508 + 104 = 612 $\frac{508}{612} = 83\%$ eff. seg. loss.

Test input Seg. loss input Stray loss

610.1 — 612 = −1.9 = −0.19% of normal load output.

TABLE VI

TWO-UNIT SET—1120-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR CONNECTED TO A 1000-KW., 250-VOLT DIRECT-CURRENT GENERATOR

50 PER CENT LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Dev. from mean
1	342.25	9980	29.15	0.188
2	346.25	10200	29.43	0.092
3	341.25	10080	29.55	0.212
4	340.25	9990	29.35	0.012
5	337.25	9850	29.21	0.128
Average	341.65	10020	29.388	0.1264 / $\sqrt{5} \times 29.388$ = ±0.193%

Ratio of trans. 1784

Mult. fact of shunts 50.6

Kw. 608.9 504.4 $\frac{504.4}{608.9}$ = 82.9% eff. input-output.

Test output Seg. loss Seg. loss input

504.4 + 104 = 608.4 $\frac{504.4}{608.4}$ = 83% eff. seg. loss.

Test input Seg. loss input Stray loss

608.9 — 608.4 = +0.5 = +0.5% of normal load output.

TABLE VII

TWO-UNIT SET—1120-KV-A., 6600-VOLT SYNCHRONOUS MOTOR CONNECTED TO A 1000-KW., 250-VOLT, DIRECT-CURRENT GENERATOR

75 PER CENT LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Dev. from mean
1	496.4	15700	31.60	0.145
2	494.4	15650	31.70	0.045
3	501.4	15910	31.78	0.035
4	499.4	15890	31.80	0.055
5	499.4	15850	31.79	0.045
6	495.4	15730	31.70	0.045
7	495.4	15750	31.78	0.035
8	494.4	15710	31.81	0.065
Average	497.02	15774	31.745	0.0587
				$\frac{0.0587}{\sqrt{8} \times 31.745} = \pm 0.065\%$

Ratio of trans. 1778.6

Mult. fact. of shunts 48.6

Kw. 884.1 768 $\frac{768}{884.1}$ = 86.8% eff. input-output.

Test output 768 + Seg. loss 114.6 = Seg. loss input 882.6 $\frac{768}{882.6}$ = 87% eff. seg. loss.

Test input 884.1 — Seg. loss input 882.6 = Stray loss +1.5 = +0.15% of normal load output.

TABLE VIII

TWO-UNIT SET—1120-KV-A., 660-VOLT, SYNCHRONOUS MOTOR CONNECTED TO A 1000-KW., 250-VOLT, DIRECT-CURRENT GENERATOR

75 PER CENT LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Dev. from mean.
1	494.6	15110	30.59	0.134
2	494.6	15100	30.57	0.114
3	489.6	14850	30.39	0.066
4	492.6	14900	30.23	0.226
5	493.6	15040	30.50	0.044
Average	493	15000	30.456	0.1168
				$\sqrt{5} \times 30.456 = \pm 0.171\%$

Ratio of trans. 1777.3

Mult. fact. of shunts 50.4

Kw. 876.4 756 $\frac{756}{876.4}$ = 86.4% eff. input-output.

Test output 756 + Seg. loss 114.2 = Seg. loss input 870.2 $\frac{756}{870.2}$ = 86.9% eff. seg. loss.

Test input 876.4 — Seg. loss input 870.2 = Stray loss +6.2 = +0.62% of normal load output.

TABLE IX

TWO-UNIT SET—1120-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO A 1000-KW., 250-VOLT, DIRECT-CURRENT GENERATOR

NORMAL LOAD

Obs. No.	Input Wm. + kw. field / ratio trans	Output millivolts × volts	Ratio	Dev. from mean
1	675.3	21800	32.23	0.165
2	647.3	20780	32.10	0.035
3	656.3	21000	32	0.065
4	658.3	21110	32.09	0.025
5	657.3	21070	32.03	0.035
6	656.3	21030	32.01	0.055
7	655.3	21030	32.10	0.035
8	653.3	20970	32.11	0.045
9	655.3	21000	32.01	0.055
10	663.3	21150	31.89	0.175
11	657.3	21040	32.01	0.055
12	660.3	21200	31.99	0.075
13	663.3	21400	32.29	0.235
14	658.3	21190	32.19	0.125
15	661.3	21100	31.92	0.145
Average	658.57	21125	32.065	0.0884 / $\sqrt{15} \times 32.065$ = ±0.071%

Ratio of trans. 1775.3

Mult. fact. of shunts 48.63

Kw. 1169.2 1027.1 $\frac{1027.1}{1169.2}$ = 87.85% eff. input-output.

Test output Seg. loss Seg. loss input

1027.1 + 129.2 = 1156.3 $\frac{1027.1}{1156.3}$ = 88.8% eff seg. loss.

Test input Seg. loss input Stray loss

1169.2 — 1156.3 = +12.9 = +1.29% of normal load output.

TABLE X

TWO-UNIT SET—1120-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO A 1000-KW., 250-VOLT DIRECT-CURRENT GENERATOR

NORMAL LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Dev. from mean
1	659.9	21570	32.70	0.58*
2	662.9	21220	32.05	0.00
3	653.9	20940	32.09	0.04
4	658.9	21090	32.19	0.14
5	654.9	20980	32.03	0.02
6	655.9	21080	32.12	0.07
7	657.9	21200	32.21	0.16
8	662.9	21060	31.08	0.25
9	659.9	21180	32.09	0.04
10	656.9	20960	31.90	0.15
Average (without No. 1)	658.2	21179	32.05	0.097
				$\sqrt{9} \times 32.05 = \pm 0.107\%$

Ratio of trans. 1775.3
Mult. fact. of shunts 48.63

Kw. 1170.1 1027.7 $\frac{1027.7}{1170.1}$ = 87.8% eff. input-output.

Test output 1027.7 + Seg. loss 129.2 = Seg. loss input 1156.9 $\frac{1027.7}{1156.9}$ = 88.6% eff. seg. loss

Test input 1170.1 — Seg. loss input 1156.9 = Stray loss +13.2 = +1.32% of normal load output.

TABLE XI

TWO-UNIT SET—1120-KV-A., 6600-VOLT, SYNCHRONOUS MOTOR, DIRECT-CONNECTED TO A 1000-KW., 250-VOLT, DIRECT-CURRENT GENERATOR

NORMAL LOAD

Obs. No.	Input Wm. + kw. field / ratio trans.	Output millivolts × volts	Ratio	Dev. from mean
1	654.9	20250	30.98	0.09
2	647.9	20100	31	0.11
3	650.9	20210	31.02	0.13
4	650.9	20160	30.95	0.06
5	650.9	20150	30.95	0.06
6	655.9	20166	30.75	0.14
7	654.9	20140	30.75	0.14
8	654.9	20250	30.95	0.06
9	654.9	20220	30.90	0.01
10	653.9	20210	30.95	0.06
11	651.9	20120	30.85	0.04
12	656.9	20320	30.90	0.01
13	654.9	20280	30.98	0.09
14	658.9	20300	30.82	0.07
15	655.9	20320	30.95	0.06
16	652.9	20100	30.80	0.09
17	655.9	20240	30.85	0.04
18	652.9	20100	30.80	0.09
19	649.9	20000	30.79	0.10
20	649.9	20050	30.82	0.07
Average	653.5	20184	30.89	$\frac{0.076}{\sqrt{20} \times 30.89} = \pm 0.055\%$

Ratio of trans. 1775.3

Mult. fact. of shunts 48.63

Kw. 1159.7 1017.3 $\frac{1017.3}{1159.7} = 87.7\%$ eff. input-output

Test output 1017.3 + Seg. loss 129.2 = Seg. loss input 1146.5 $\frac{1017.3}{1146.5} = 88.7\%$ eff. seg. loss.

Test input 1159.7 — Seg. loss input 1146.5 = Stray loss +13.2 = +1.32% of normal load output.

Brush and bearing friction including windage 28.87 kw.

TABLE XII

THREE-UNIT SET—1450-KV-A., 2300-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO TWO 500-KW., 1200-VOLT, DIRECT-CURRENT GENERATORS

50 PER CENT LOAD

Obs. No.	Input			Output kw.	Ratio	Deviation from mean
	W_1	W_2	$W_1 + W_2$			
1	172	67	239	496.37	2.074	0.024
2	172	70	242	513	2.118	0.020
3	170	70	240	493.46	2.052	0.046
4	170	67	237	499.80	2.108	0.010
5	174	69	243	511.85	2.182	0.076*
6	171	68	239	502.82	2.101	0.003
7	170	66	236	493.71	2.088	0.010
8	171	67	238	503.94	2.115	0.017
9	168	65	233	491.14	2.106	0.008
10	170	67	237	502.88	2.120	0.012
Average (Without 5)	170.47	67.44		499.66	2.098	0.0167
						$\sqrt{9} \times 2.098$
						= 0.265%

Phase angle correction factor	0.9982	0.9705			
C. T. ratio	120.4	120.3			
P. T. ratio	19.88	19.90	Kw. input		
Kw	407.3	156.69	563.99		$\frac{499.66}{571.47}$ = 87.43% eff. input-output
Sep. exc. field			7.48		
Total input			571.47		
Total output				499.66	

Test output 499.66 + Seg. loss 68.42 = Seg. loss input 568.08 $\frac{499.66}{568.08}$ = 87.95% eff seg. loss

Test input 571.47 — Seg. loss input 568.08 = Stray loss +3.39 kw. = +0.34% of normal load output.

TABLE XIII

THREE-UNIT SET—1450-KV-A., 2300-VOLT, SYNCHRONOUS MOTOR DIRECT CONNECTED TO TWO 500-KW., 1200-VOLT, DIRECT-CURRENT GENERATORS

75 PER CENT LOAD

Obs. No.	Input			Output kw.	Ratio	Deviation from mean
	W_1	W_2	W_1+W_2			
1	253	103	356	770.17	2.162	0.005
2	250	98	348	745.05	2.14	0.017
3	250	99	349	751.56	2.15	0.007
4	250	97	347	755.58	2.175	0.018
5	250	98	348	748.82	2.147	0.010
6	250	97.5	347.5	751.79	2.164	0.007
7	249	97.5	346.5	743.78	2.143	0.014
8	249	97.5	346.5	745.96	2.152	0.005
9	250	98	348	757.77	2.176	0.019
10	250	97.5	347.5	751.10	2.163	0.006
Average	250.1	98.3		752.158	2.157	$\frac{0.0108}{\sqrt{10}\times 2.157} = \pm 0.1586\%$

Phase angle corr. factor	0.99804	0.9719			
C. T. ratio	120.1	120			
P. T. ratio	19.88	19.9	Kw. input		
Kw.	596.1	228.13	724.23		
Sep. exc. field			8.085	$\frac{752.158}{832.315}$	= 90.37% eff input-output
Total input			832.315		
Total output				752.158	

Test output — Seg. loss — Seg. loss input

752.158 + 79.871 = 832.029 $\frac{752.158}{832.029}$ = 90.508% eff. seg. loss.

Test input — Seg. loss input — Stray loss

832.315 — 832.029 = +0.286 kw. = +0.286% of normal load output.

TABLE XIV

THREE-UNIT SET—1450-KV-A., 2300-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO TWO 500-KW., 1200-VOLT, DIRECT-CURRENT GENERATORS

NORMAL LOAD

Obs. No.	Input			Output kw.	Ratio	Deviation from mean
	W_1	W_2	W_1+W_2			
1	338	132	470	1021.8	2.178	0.001
2	330	124	454	992.7	2.183	0.004
3	331	130	461	1001	2.172	0.007
4	333	137.5	470.5	1026.3	2.181	0.002
5	330	137	467	1020.1	2.183	0.004
6	330	136	466	1014.9	2.179	0.000
7	330	137	467	1020.9	2.183	0.004
8	326	131	457	994.7	2.173	0.006
9	330	131	461	1003.3	2.176	0.003
10	330	131	461	1002.8	2.175	0.004
11	330	132.5	462.5	1010.8	2.187	0.010
12	332	131	463	1004.9	2.173	0.006
13	334	134	468	1020.2	2.182	0.003
14	330	132	462	1005.6	2.179	0.000
15	329	132	461	1016	2.204	0.024*
16	331	134	465	1011.6	2.175	0.004
17	330	132.5	462.5	1005.1	2.175	0.004
18	329	128	457	1000.7	2.190	0.011
19	330	131.5	461.5	998.7	2.162	0.017
20	330	131.5	461.5	1001.2	2.189	0.011
Average (without 15)	330.74	132.37		1008.28	2.179	$\frac{0.0053}{\sqrt{19}\times 2.179} = \pm 0.574\%$

Phase angle corr. factor	0.99804	0.9719	
C. T. ratio	119.8	119.8	
P. T. ratio	19.88	19.9	Kw. input
Kw.	785.98	306.55	1092.53

Sep. exc. field	10.832		
Total input	1103.36	1008.28 / 1103.36	= 91.39% eff. input-output
Total output		1008.28	

Test output		Seg. loss		Seg. loss input	
1008.28	+	96.068	=	1104.348	$\frac{1008.28}{1104.348}$ = 91.34% eff. seg. loss.

Test input		Seg. loss input		Stray loss	
1103.36	—	1104.348	=	− 0.988	= —0.0988% of normal load.

Brush and bearing friction including windage = 18.55 kw.

TABLE XV

THREE-UNIT SET—1450-KV-A., 2300-VOLT, SYNCHRONOUS MOTOR DIRECT-CONNECTED TO TWO 500-KW., 1200-VOLT, DIRECT-CURRENT GENERATORS

125 PER CENT LOAD

Obs. No.	Input			Output kw.	Ratio	Deviation from mean
	W_1	W_2	$W_1 + W_2$			
1	407	165	572	1259.69	2.200	0.024
2	410	168	578	1259.32	2.181	0.005
3	407	168	575	1250.79	2.178	0.002
4	410	168	578	1249.87	2.164	0.012
5	405	167	572	1246.75	2.178	0.002
6	405	167	572	1267.54	2.216	0.036*
7	412	169	581	1267.25	2.181	0.005
8	414	170	584	1252.96	2.148	0.028
9	406	167	573	1248.80	2.180	0.004
10	412	169	581	1262.16	2.171	0.005
Average (without 6)	409.2	167.9		1255.29	2.176	0.0097
						$\frac{0.0097}{\sqrt{9} \times 2.176}$ = 0.148%

Phase angle corr. factor	0.9980	0.9719			
C. T. ratio	119.6	119.6			
P. T. ratio	19.88	19.90	Kw. input		
Kw.	970.96	388.37	1359.33		
Sep. exc. field			12.338	$\frac{1255.29}{1371.668}$	= 91.512% eff. input-output
Total input			1371.668		
Total output				1255.29	

Test output 1255.29 + Seg. loss 118.025 = Seg. loss input 1373.315 $\frac{1255.29}{1373.315}$ = 91.409% eff. seg. loss.

Test input 1371.668 — Seg. loss input 1373.315 = Stray loss —1.647 kw. = —0.165% of normal load output.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

SOURCES OF ERROR IN THE EFFICIENCY DETERMINATION OF ROTATING ELECTRIC MACHINES

BY ELMER I. CHUTE AND WILLIAM BRADSHAW

The efficiency of any apparatus is the ratio of its net power output to its gross power input. According to the Standardization Rules of this Institute this may be determined with certain limitations by either of two methods, by the input-output method or by the summation of separate losses.

By the first method the input and output are to be measured directly, either mechanically or electrically as the case may be; by the second the separate losses are to be determined either individually or collectively, and, in the case of generators, added to the output to give the input, or, in the case of motors, subtracted from the input to give the output. In either method the efficiency equals the output divided by the input.

To determine the loss values, measurements of resistance, core and frictional losses are involved, quite elaborate tests being usually required to determine the latter two. In the input-output test two measurements only are required, which to the uninitiated seem as though they should be obtained without any special preparation whatever, especially where both values to be measured are electrical, as will be assumed in this paper.

If all measurements could be taken with perfect accuracy there could be no discussion whatever on this subject, or even if all inaccuracies affected the final results in equal proportion, one would be as reluctant to take separate loss measurements for efficiency calculations as some are now to take input-output tests. But this is far from the case.

Inaccurate readings of power input to the driving motor, while

determining the core and frictional losses, are practically the only sources of error in loss measurements. These errors, moreover, enter into the result only indirectly. In a paper* presented at the annual convention at Boston, it was shown from data on a large number of machines that even in the most extreme case when the effect is largest, an error of five per cent in the actual readings taken affects the efficiency by only one-half of one per cent. The effect in the average case is less than two tenths of one per cent. The real variation is probably much less than this, for the five per cent error assumed is a very high value seldom occurring even in commercial practise.

In the input-output test, on the other hand, all errors in measurement enter directly into the result. The five per cent above assumed (and it is as logical to assume it in one case as in the other, under equal conditions) would probably affect the efficiency at least five, if not ten per cent, depending on whether the errors in measurement of the output and input were cumulative or tended to neutralize. The probability of this may be more apparent from the following analysis of all the incorrect conditions that might exist.

Input correct,	output high	—	Effect directly proportional to error.	
" "	" low	—	" " " " "	
" high	" correct	—	" " " " "	
" low	" "	—	" " " " "	
" high	" low	—	" " to sum of error	
" low	" high	—	" " " " "	
" low	" low	—	Errors tend to neutralize	
" high	" high	—	" " "	

It is apparent, then, that if efficiencies as consistent as those determined by the loss method are to be obtained, every precaution conceivable must be taken that the observations made, or readings taken, are as little in error as possible. It is this necessity that offsets the otherwise apparent simplicity of the input-output method, and renders the test far more elaborate and costly to conduct than any other method of efficiency measurement.

A brief examination of the sources of error will bring out some of the precautions that must be observed. These may be classified as follows:

**Determination of Power Efficiency of Rotating Electric Machines* E. M Olin, TRANS. A. I. E. E., Vol. XXXI, p. 1695.

a. Instrument errors.
   1. An unsuitable selection of meters or associated apparatus.
   2. Inaccuracies of calibration.
   3. Improper location or use of the instruments.

b. Observation errors.
   1. Personal errors.
   2. Errors due to fluctuation of meter indicators, depending on character of circuit.

c. Errors due to varying conditions of operation.
   1. Change in constant losses.
   2. Comparison with separate loss values not made under same conditions.

Instrument errors may be avoided to a large extent in any first class laboratory or manufacturing plant, but become of vital importance in isolated stations where suitable instruments are not available, or in plants when apparatus is much crowded or where very heavy currents are the rule.

Measuring instruments must be selected with the conditions thoroughly in view. Well damped indicating instruments have proved the best in practise. Watt-hour meters placed on both the incoming and outgoing lines would naturally seem to be the best solution of the problem, but repeated tests with the best types of available instruments have not proved as satisfactory as those taken with indicating meters.

The accurate calibration of the meters used is essential. For ordinary work the accuracy of one-half of one per cent of the full scale reading at any point on the scale, which is the usual guarantee, is sufficient, but in an input-output test even this error, considering the number of meters used, may lead to an error of two per cent or more, in the efficiency of the apparatus under test. Meters if used with care can be depended on to hold this accuracy very well, but to make certain that no change in calibration has occurred during a test it is always advisable to check them at the end as well as the beginning of the test.

The proper locating of meters, especially those of the moving coil type, must be given careful consideration. They should rest on a firm, rigid support and be so located as to be free from any external field effects. It must not to be assumed that even meters of the shielded types can be exposed indiscriminately to stray fields. As a general rule the same precautions should apply to them as to others.

When one considers the large number of meters necessary on such tests, the necessity of eliminating or accounting for even the most minute errors in them is evident. In the simplest case, when the incoming and outgoing power are each direct current, four meters are necessary. In the case of synchronous converters, or motor-generators other than d-c. to d-c., the number is increased to at least seven and possibly ten, all of which enter directly into the result. In addition to the measuring instruments a number of series and potential transformers are usually required. These, however, may be very accurately calibrated provided the proper equipment is available, and can be depended on to hold their calibration well. The name-plate ratio in the case of current transformers when used at from 70 to 100 per cent of their rated load is only accurate within one-half of one per cent. Potential transformers when properly compensated may be considered accurate to three-tenths of one per cent.

Errors in reading indicating instruments vary, depending to a large extent on the variations in the circuit in which they are connected. The ideal condition, of course, is where the characteristics of the circuit permit the indicator of the meter to move at once to its proper location, and remain there as though fixed. In such cases the error is due to the inability of the average reader to locate the indicator closer than to possibly 0.1 of a division. This would introduce an error of approximately 0.13 per cent in the reading if taken at about the middle of a scale of 150 divisions. Such an error could readily be neglected if occurring in one meter only, but if such an error should exist in each of the meters used and the effect were cumulative with respect to the final result, it is evident that the error would soon be of considerable magnitude.

This ideal condition, however, may be said never to exist, the nearest approach to it being in cases where the source of power is not more than one step removed from a well regulated prime mover on which there is no variable load, and liberally designed grid resistances or a water rheostat used to absorb the power output of the apparatus under test. Under this condition the pointers of the meters will swing back and forth over a small part of the scale, perhaps only a division or two. The effort of estimating the position of the pointer is added to the former effort to divide up the space correctly. The liability to error therefore is increased materially.

However, under the usual conditions met with in commercial

work, power must be taken from generators serving many other machines, the load on which is likely to be quite variable. Loading these machines, especially the larger sizes, on water rheostats or resistances is not a desirable economical proposition. Loading-back methods, therefore, are ordinarily resorted to, so that only the losses have to be supplied from the prime mover. Under such conditions the swinging of meter pointers will be greatly increased. It not infrequently occurs that meters must be read while their indicators are wandering more or less irregularly over as much as 25 per cent of the scale. That errors of reading increase much more rapidly than the increase in length of the indicator swing is not at all improbable, though no accurate data are available as to the probable law.

If there were no compensation of errors, consistent results from data obtained under such conditions would be out of the question. It may be proved by certain laws of mathematics that the probable variation of the average of a number of readings differing widely among themselves is but little from the true but unknown value. However, the accuracy is not increased in direct proportion to the number of readings, but in proportion to their square root, so that very little is gained by taking more than ten or fifteen readings. In view of this it is customary to take readings in series of ten, a simultaneous reading being taken of all meters involved, at intervals of about ten seconds, until ten are obtained. The average of these is considered as the nearest approach to the true value. In a certain case where the maximum variation from the mean value of ten readings was 1.5 per cent, the variation, as computed from the mathematical laws previously referred to, was less than 0.2 per cent from the true, but unknown, value. This would all have been very well if the average of ten other such readings taken under as nearly as possible the same conditions had not given 1.7 per cent difference in efficiency, and according to the same laws was also accurate to within 0.2 per cent. As this is the condition that is continually arising, it is evident that even the laws of chance can give us very little help in the solution of the problem.

It would seem as though an actual change in the efficiency of the apparatus had taken place, due possibly to a change in operating conditions, or in the constant losses of the machines. But when one stops to analyze the magnitude of any such possible change one finds a considerable discrepancy still unaccounted

for. However, such changes must not be ignored, especially in the case of tests on synchronous converters, where the total losses are but a very small proportion of the output of the machine. To make sure that no change of any consequence has taken place it is always well to check the frictional losses both before and after the test. This also insures that the determination of efficiency by separate losses, which is the best criterion available as to the accuracy of the input-output test, is made under identically the same conditions.

It is conceded that the efficiency by the "summation of losses" is not the true operating efficiency of the apparatus, as no account is usually taken of the so-called "load" or "stray" losses. It has been proposed to account for this discrepancy by a system of factors that depend for their magnitude on the type of apparatus. As this additional loss under load consists of additional core and copper losses, due to distorted field effects and eddy currents, it is suggested that the factor required be applied to their sum. In another paper* at present before this Institute, the magnitude and determination of this constant have been discussed and its limits experimentally determined to some extent. It is interesting to compare the probabilities of error of this method with those already existing.

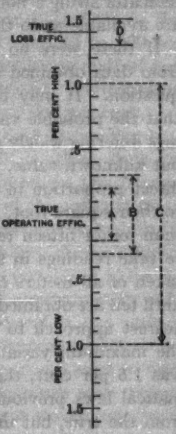


FIG. 1

Assume a concrete case of a 500-kw. direct-current generator the losses of which total 10 per cent or 50 kw., and that they are measured with an accuracy of 2 per cent. Of this 50 kw., 70 per cent., or 35 kw., will be assumed as a fair value of the sum of the core and armature copper losses. The value of the load factor for normal load, as suggested in the paper previously referred to, is about 1.3 for direct-current machines. It seems that this can be determined within ± 2 per cent or, in other words, may vary between 1.27 and 1.33.

Using the values assumed above, it will be found that the efficiency by losses at normal load will be between 91.6 and 91.8

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson; page 479 of this volume.

and after applying the load factors, allowing for the above-mentioned variation, the efficiencies will be between 90 and 90.6 per cent.

This difference depends chiefly on the ratio of the sum of the core and the copper losses to the total loss. As this ratio decreases with the larger machines, or in those whose total losses are a small proportion of the output, the variations are reduced. The input-output test shows just the opposite tendency, for the same error is liable with small losses as with large ones and therefore becomes a much larger factor in the final efficiency.

The foregoing conditions may be represented graphically as in Fig. 1, in which *A* represents the probable limit of error in an input-output test, conducted on stable circuits and liberally designed water rheostats or grid resistances, in which all possible precautions have been taken. The limits represented by *C* cover the probable limits of error where this test is taken on commercial circuits, but where first-class testers are reading the meters and conducting the test. Under other conditions the results are entirely too variable to be represented in such a diagram. The limits covered by *B*, mark the probable limit of error of efficiencies determined from losses, in connection with correcting factors, in which the correcting factors have been determined from input-output tests as conducted in the manner *A*, or from other more accurate methods whenever possible. *D* represents the possible variation in the loss efficiency.

It is apparent that input-output tests under the best conditions can be taken with a considerable degree of accuracy, but does the additional accuracy gained over the simple method suggested warrant the industry incurring the larger additional cost of equipment and labor necessary to conduct such tests?

Efficiency values, while they should represent average operating conditions as nearly as possible, are of especial value for the comparison of the product of different manufacturers. Methods, then, that can be standardized and easily duplicated should be used in the determination of this value, so that the product of all will be on the same basis.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

BRUSH FRICTION AND CONTACT LOSSES

BY H. F. T. ERBEN AND A. H. FREEMAN

The rapid development of modern electrical apparatus has necessitated most careful selection of brushes to meet the varying conditions of current, voltage, speed, etc., which in turn has required a very thorough study of their characteristics and losses.

The present Standardization Rules (Sections 103, 111, 112) fail adequately to cover this most important subject, and appreciating the necessity for more definite methods of determining brush losses, an exhaustive series of tests has been conducted during the past year, results of which are herewith presented.

The two sources of loss to be considered, either on commutators or on collectors, are brush friction and brush contact drop.

Friction. The friction of two bodies in sliding contact is governed by—1st, the nature of the materials, 2nd, the pressure forcing them together. The actual value of this friction (expressed in watts or h.p.) can only be determined by trial. Theoretically, the magnitude of the friction loss between two materials varies directly with the pressure and, therefore, the ratio of the force tending to retard the relative movement of the two bodies to the force pressing them together (coefficient of friction) should remain constant for all pressures less than that producing crushing or grinding of the materials.

Determination of Friction. To determine the coefficient of friction, a commutator was mounted on a shaft directly driven by an adjustable speed motor of such size that the maximum total load was less than the rated capacity of the motor. As many brushes as possible were assembled on the commutator in order that the brush friction might be a large part of the total load. Tests were made on numerous grades of brushes, in vari-

ous types of brush holders, operating in both directions of rotation and through wide ranges of speed and pressure. The data thus obtained give the friction of brushes when carried in commercial brush holders. We are not yet prepared to give the full and complete results of these tests, as many of the results are now being verified. We show, however, on Curve 1 the coefficient of friction obtained at various speeds with one type of graphite brush operated at an angle of 37½ deg. leading. Fig. 1 shows what is meant by various angles, leading and trailing.

Test was also made to show the effect of temperature on coefficient of friction by enclosing a commutator in an asbestos-lined box, placing resistance grids under the commutator for a source of heat and piping a blower to the box to regulate and hold the temperature at various values. Tests were made at various speeds and at 40, 60, 75 and 100 deg. cent., and it was found that the change in input to motor over wide ranges in temperature was so slight as to be negligible in commercial applications.

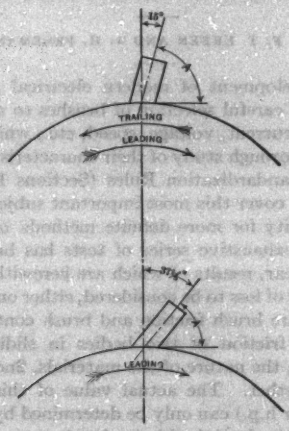


FIG. 1

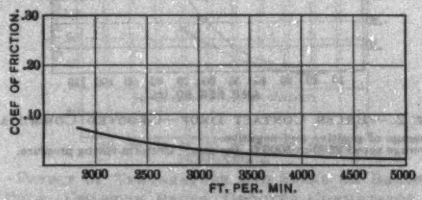
We will later present similar curves showing coefficient of friction values with various types of brushes when operated at different angles.

Application of Data on Brushes. Assuming the coefficient of friction as shown on curve to be applicable to the type of brush holder used, the friction should be calculated, as follows:

$$\frac{P \times S \times V \times F \times 746}{33{,}000} = W$$

When W = Watts loss, brush friction.
P = Total applied pressure on brushes.
V = Velocity, commutator or ring, in ft., per. min.
F = Coefficient of friction.
S = Sine of angle A (Fig. 1).

For example, on a commutator 25 in. (63.5 cm.) in diameter running 2500 ft. (763 m.) per minute with 60 grade S brushes



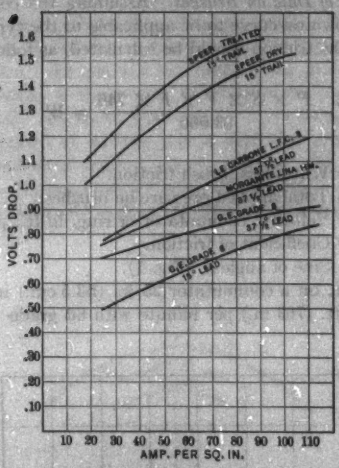
CURVE 1.—COEFFICIENT OF FRICTION, GRADE S BRUSHES
Angle 37½ deg. leading. Approx. 2 lb. per brush applied pressure

at an applied pressure of 2 lb. (0.907 kg.) per brush operating at 37½ deg. angle.

F = 0.05 (Curve 1).
S = 0.783.

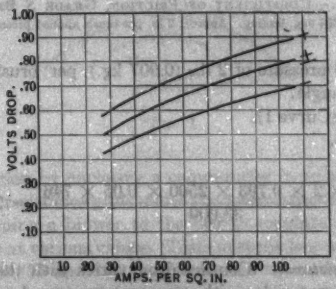
$$W = \frac{60 \times 2 \times 0.793 \times 2500 \times 0.05 \times 746}{33{,}000} = 270 \text{ watts}$$

Contact Resistance. Contact drop varies with the characteristics of the materials, with temperature, speed and pressure. Generally, the volts drop under the brush which is positive to the rotating element (negative brush on a d-c. generator) is greater than under the brush which is negative to commutator (positive brush on generator.) Curve 2 shows average volts drop with



CURVE 2.—BRUSH CONTACT DROP—GROOVED COMMUTATOR

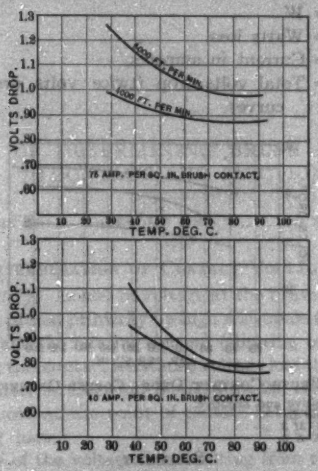
Average of positive and negative.
Average speed 2500 to 5000 ft. per min. Uniform spring pressure.



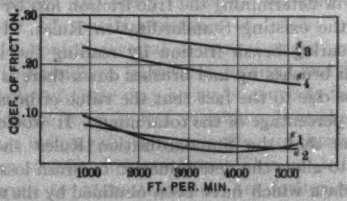
CURVE 3.—BRUSH CONTACT DROP—GRADE S BRUSHES—GROOVED COMMUTATOR—65 DEG. CENT.

Average speed 2500 to 5000 ft. per min. 15 deg. lead.
+ = Current from brush to copper.
− = Current from copper to brush.

carbon and graphite brushes on grooved commutator. Curve 3 shows volts drop, positive and negative, and average between them. Curve 4 shows combined effect of temperature and speed



CURVE 4.—EFFECT OF TEMPERATURE AND SPEED ON BRUSH CONTACT DROP—GRAPHITE BRUSH, GROOVED COMMUTATOR



CURVE 5.—COEFFICIENT OF FRICTION, COPPER-GRAPHITE BRUSHES

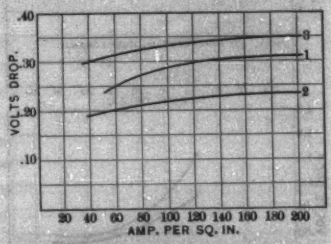
1—Metite grade *L*.
2—Lecarbone Metal, No. 2.
3— " *K K* 3.
4—Morganite *C M* 3.

on contact drop with graphite brushes. Curve 5 shows coefficient of friction of copper-graphite brushes such as metite, morganite CM-3, etc. Curve 6 shows contact drop with copper-

graphite brushes or same grades. The data on contact drop shown on accompanying curves give the average of the drop under brushes of both polarities. The watts loss from contact resistance will then be

$$C\,V = W$$

in which W = Watts loss.
C = Current in amperes.
V = Total volts drop (twice volts drop shown on curve).



CURVE 6.—BRUSH CONTACT DROP—COPPER-GRAPHITE BRUSHES

Average of positive and negative.
1—Metite, grade *L*.
2—Morganite *C M* 3.
3—Lecarbone *K K* 3.

SUMMARY

It is apparent from the foregoing that the niceties of adjustment found necessary in obtaining coefficient of friction show the hopelessness of determining the true friction loss by the method outlined in the existing Standardization Rules. It is evident that in measuring brush friction by reading the input to the machine with brushes up and brushes down there is a great element of error due to the fact that the value of brush friction is such a small percentage of the total input. It would, therefore, seem obvious that the Standardization Rules should be so amended as to allow the determination of brush losses by calculation from data which have been obtained by the most reliable methods and approved by the Institute.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

METHODS OF DETERMINING BRUSH LOSSES DUE TO CONTACT AND FRICTION

BY H. R. EDGECOMB AND W. A. DICK

1—Determination of Contact Voltage Losses

I. *Introductory.* Losses in voltage at the brushes of an electric machine are caused primarily by high resistance contact between the brushes and the rotating element (slip ring or commutator). Augmenting this contact resistance voltage loss there is, as stated by F. W. Carter, in *Electrical World*, June 29, 1912, an ionization voltage induced at the point of contact between the brush and the rotating part.

The value of the voltage loss resulting from these two causes is affected by: (a) composition and physical characteristics of brush; (b) composition and surface of rotating part; (c) fit of brush in holder; (d) brush pressure; (e) peripheral speed of rotating part; (f) specific resistance of brush; (g) design conditions which control reversal of current under brush; (h) temperature; (i) humidity; (j) current density; and (k) lubrication. The first seven of these may be made constant for a given test, the last four are more or less variable. It is the fact that the test readings indicate the composite effect of these variables that makes them so difficult to analyze. This has led certain brush manufacturers to state that they are fortunate if they can check results within 25 per cent. Our experience bears out this statement.

II. *Apparatus.* The ideal test apparatus for determining voltage losses due to contact should have facilities for varying pressure, speed, composition of rotating part, temperature, humidity, current density and lubrication, and for accurately measuring degree of variation. Specific resistance, composition

of brush and design conditions are of course constant for any given test. The range of variation should be as follows: brush pressure, 0 to 10 lb. per sq. in. (0 to 703 g. per sq. cm.); peripheral speed, 500 to 10,000 ft. (152 to 3048 m.) per. min.; composition of rotating part, copper, brass, bronze, steel and cast iron for collector rings and copper-mica, plain and undercut, for commutators; temperature, up to 100 deg. cent.; humidity up to 100 per cent saturation; current density up to the glowing point of the brushes being tested. Amount of lubrication may be measured by weight. It is assumed that apparatus for these tests must be sufficiently massive to prevent vibration and that the electric circuits should be of ample cross-section. Apparatus should be direct-connected to a source of power in preference to being belted, as the variation in speed and the vibration due to the belt sometimes seriously affect the test.

Most testing outfits are arranged to provide for measuring all these variables and for controlling all except humidity and temperature. Humidity has such an important part in voltage losses that unless it is controlled the record of a test will be seriously affected, and as far as we know, no attempt to do this has been made up to this time. For the control of temperature, however, Dr. Arnold has used an electrically heated collector ring and his researches as recorded in *Elektrotechnische Zeitschrift*, March 21, 1907 have established a very useful set of facts concerning effect of temperature on commutation.

The apparatus used in getting the results later referred to (Figs. 1 and 2,) consists of a d-c. generator, the commutator of which has its bars short-circuited by a number of turns of copper wire soldered around the neck. Six ingoing and six outgoing brushes were used. These were well plated and shunted. Fine copper wire was bound tightly into a groove around the brush near the contact point and insulated leads were brought out along a beveled corner of the brush. A power-operated controller connected the brushes consecutively with a graphic voltmeter making records of about 15 sec. duration for each brush. The return was through a copper leaf brush bearing on the shaft which was grounded to the commutator. The records consisted of a series of dots, and indicate quite accurately the range of travel of the voltmeter needle.

Temperature measurements were made with the potentiometer, using thermocouples inserted in the brushes near the contact surface. Current was measured by an indicating ammeter. Humidity was measured by a hygrodeik.

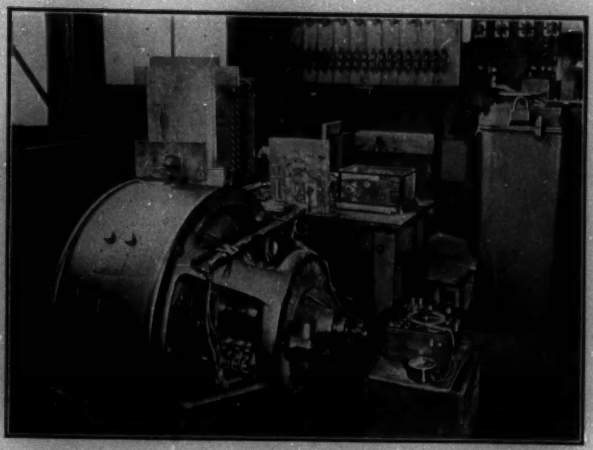


FIG. 1 [EDGECOMB AND DICK]

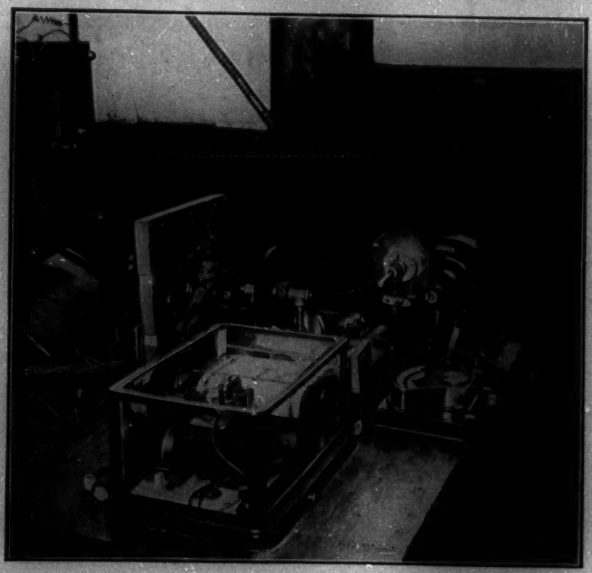


FIG. 2 [EDGECOMB AND DICK]

The graphic meter was frequently calibrated and on its record strip was entered the log of the test, including current density, voltage drop for each brush, temperature, humidity and individual brush pressure.

III—*Surface Variations.* In addition to the variations in brush drop due to causes previously mentioned, the graphic meter has identified two other sources from either of which there might be at least 50 per cent variation on voltage loss.

At the beginning of the test the brushes were fitted as carefully as possible and the machine was run for a day without load to insure a good brush contact. The current was then applied and after a steady temperature was attained it was noted that the voltmeter showed relatively small momentary fluctuation,

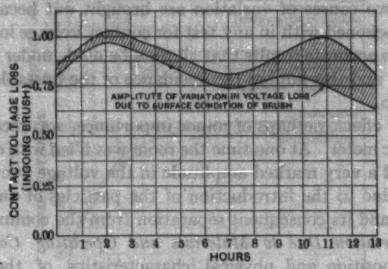


FIG. 3

about 6 per cent (Fig. 3.) The test was continued for 13 hours and during this time the fluctuation increased to 29 per cent. This was checked several times by running the commutator without current for about ten hours and repeating test with practically the same results. During these tests nothing was done to the surface of the commutator.

It is evident that this fluctuation in voltage drop is related to the surface condition of the brush due to the passage of current, as it was controlled by polishing the brush without voltage. We may assume that a disintegrating action takes place, due to the passage of current, which either reduces the actual surface contact or which momentarily separates the brush from the commutator, or which causes migration of the points of contact over paths of greater or less resistance.

The second source of variation has to do with the surface condition of the commutator. After a week's run with current on, when conditions have become as stable as possible the commutator was wiped with clean filter paper and the removal of the surface coating caused an instantaneous increase in the voltage drop, particularly at the ingoing brush. Return to normal conditions occurred in about an hour. Analysis of the material removed showed it to be all carbon, none of the copper oxide having been removed.

As a probable explanation of this phenomenon it is suggested that the fine carbon dust which adheres to the commutator serves as a plastic medium between brush and commutator, adjusting itself to each brush, giving better contact and less voltage loss.

These two causes of variation are brought out because they must be reckoned with in any test for contact voltage loss. It is essential to accurate results that all tests be made under the same conditions and this implies the avoidance of the unstable periods referred to.

Another effect, perhaps of minor importance, was recorded by the graphic meter. At one time the room was filled with dust, and this caused a very marked amplitude in the voltage fluctuations, probably due to the introduction of the particles of dust under the brush and its consequent separation from the commutator.

IV. *Variation Due to Materials and Operating Conditions.*

a. Composition and physical characteristics of the brush: Relative density, proportion of graphitic to plain carbon, the percentage of metal, the percentage of non-conducting abrasive material in the composition, and the temperature, time and manner of firing, all play an important part in determining the contact voltage loss.

b. Composition and surface of rotating part: Voltage loss will be less for material which does not form a non-conducting oxide on its surface. It was noted that brass collector rings containing zinc became coated with an oxide which increased the contact resistance. The oxide was removed with acid and the resistance reduced. Voltage loss is probably increased by the glaze or polish which results from operating a machine.

c. Fit in holder: Continuous contact between brush and rotating part is seriously affected by the inaccuracies of fit of the brush in the brush holder.

d. Brush pressure: It is the practise of brush manufactur-

ers to make contact drop tests at the pressure considered most suitable for the brush being tested, and for this reason very few data on the effect of brush pressure are available. It is known, however, that contact voltage loss varies inversely with brush pressure and as increased pressure causes increased friction, the resulting temperature rise should further decrease the voltage loss.

e. Peripheral speed: Contact voltage loss will increase with peripheral speed because the contact between the brush and rotating part will be made less intimate by the increased jumping of brush due to irregularities on the surface of rotating part.

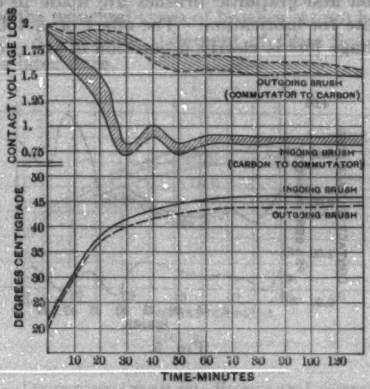


FIG. 4

f. Specific resistance of brush: Contact voltage loss may be expected to vary with the specific resistance of the brush.

g. Design conditions: This feature is not considered, as it is outside the scope of this paper.

h. Temperature: The temperature effect accompanying the passage of current through a brush-commutator circuit is shown in Fig. 4. The maximum efficient temperature appears to be determined either by the glowing point of the carbon or by the amount to which the specific resistance of the brush can be reduced by heating and not cause excessive sparking due to short-circuited coils under the brush. The most efficient point may, however, be higher than it is desirable to use in actual practise.

i. Humidity: Fig. 5 shows a somewhat remarkable relation between contact voltage loss and humidity. In a run of fifty hours the contact drop curve rises and falls with the humidity curve. The fact that the amounts of increase and decrease are not always proportional can be credited to other definite causes such as temperature, surface variation, etc.

j. Current density: Voltage loss will increase with current density.

k. Lubrication: The use of local lubrication is not viewed with favor on account of the resulting gumming of the commutator. Some manufacturers add lubricants to the brushes by impregnation and graphitic brushes are made to depend upon their graphite for lubrication. The effect of a lubricant upon contact voltage loss is clearly a question of the conductivity or

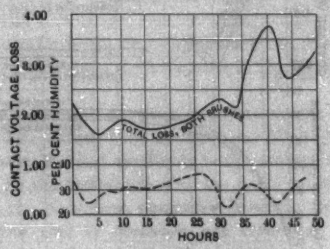


FIG. 5

non-conductivity of the lubricant used. Graphite should be a less harmful lubricant than paraffin for this reason.

V. *Conclusions and Recommendations.* When the tests which have been recorded in this paper were begun, it was with a conviction that unless the variables which have been the despair of investigators could be eliminated or controlled, very little profit would result from further tests. With means for identifying and controlling these variables, we believe results should check within 5 per cent instead of 25 per cent, and if brush manufacturers have means for accurately determining the characteristics of the brushes now being produced, they will certainly be better able to develop new brushes having better characteristics.

To arrive at a definite figure for the voltage loss due to con-

tact which may be expected from each brand of brush, it is essential that tests be made under uniform conditions, particularly as to brush pressure, peripheral speed, surface conditions, composition and diameter of rotating parts, temperature, humidity and current density.

Fig. 6 presents a typical set of curves for recording the data pertaining to each kind of brush. These include the more important characteristics: current density, temperature, pressure and contact voltage loss. Suitable multipliers are to be used to cover composition of rotating part, speed and humidity.

Because of the limited time for making tests, the actual voltage loss values for the principal types of brushes cannot be presented in this paper. A complete statement of these figures may be expected at a later date.

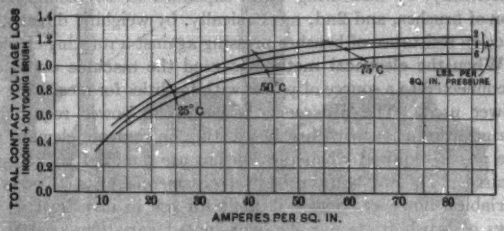


FIG. 6

2—DETERMINATION OF FRICTION LOSSES

Primarily, brush friction is the resistance to motion which occurs when the surface of a revolving commutator or slip ring slides against the surface of a stationary brush.

The problem is a mechanical one and its discussion should consider:

I. The friction formula with reference to modifications for dry surfaces.

II. Test methods and apparatus.

III. Convenient units for expression of brush friction values.

IV. Effect on brush friction of composition of revolving part of brush, and angle of brush, of surface condition of revolving part, of peripheral speed, of brush pressure and of contact area of brushes.

V. Proposed formulas and typical curves for use of designer.

I. The friction formula for perfect contact conditions is expressed as follows:

$$K = \frac{F}{N} \text{ or } F = K\,N$$

in which K = coefficient of friction.
F = force required to make one body slide on another.
N = normal pressure.

In the case of dry surfaces, F will be less than $K\,N$ up to a certain value for N, after which F will rapidly increase until seizure occurs. This feature as it affects seizure does not enter into usual brush tests because the pressures are all well below the critical point.

II. Tests for brush friction have been made in two ways: 1st, electrically, by measuring watts expended in overcoming friction of brushes, and 2nd, mechanically, by weighing directly the friction resistance of brushes pressing against a rotating element.

When the electrical method is used the machine under test is connected to a source of power with facilities for measuring the power used. The difference between the power required to maintain rotation with brushes resting on rotating element and the power required when the brushes are removed is the result desired. This method is used in all commercial tests. Too many variables, however, render it unfit for use in investigating the laws of brush friction. We have noted variations of 100 per cent within a few minutes. For this reason the comparison of commercial tests on a large number of machines gives very little reliable information.

In the mechanical method the brushes are supported in a delicately balanced cage, mounted on ball bearings and provided with an arm attached to a spring. This spring resists the tendency to revolution due to friction of brushes and its extension is measured in desired terms on a dial, the direct reading of which eliminates calculation errors. An apparatus of this kind, as used by a leading brush manufacturer, is shown in Fig 7.

If a strict comparison of the coefficients of friction of a number of brush samples is desired, more accurate results will be obtained if the rotating part is a solid ring, preferably copper, with an accurately polished surface. It must be remembered, however, that the behavior of the brush on this nearly ideal surface will be different from its behavior on a commutator having mica segments. It is suggested that this difference be accounted for

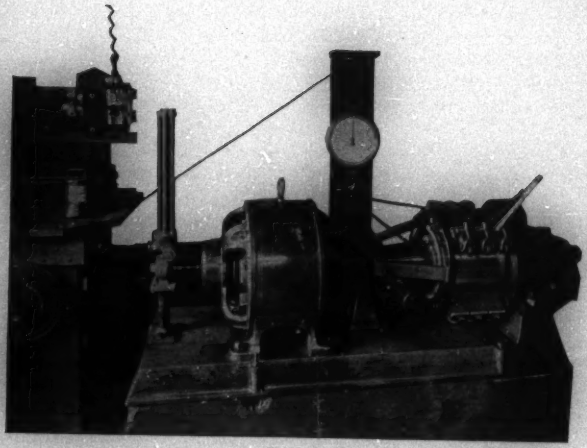


FIG. 7 [EDGECOMB AND DICK]

by a system of multipliers as follows; (a) a set of constants representing the difference between the surface of the test apparatus ring and the surface of cast iron, steel, bronze, and brass rings and of copper commutators, all assumed to be as well polished as the test ring; (b) a set of constants representing the difference between the surface of a "green" or freshly turned and sandpapered rotating part and the surface of a well polished rotating part; (c) a set of constants representing the difference in friction due to the angle of the brush.

III. The results of brush friction may be expressed in three ways: (a) coefficient of friction, the value of which may be computed from readings obtained electrically or which may be read directly from the dial in the mechanical method. (b) watts consumed due to brush friction, which is obtained, as stated, by the first test method, also by calculations to be mentioned later; (c) percentage of total input, calculated from (b).

IV. The effect of materials and operating conditions may be detailed as follows: When two materials slide on each other, their coefficients of friction vary with the nature of either or both of the materials. Each of a large number of carbon brush compositions gives a different coefficient when bearing on the same revolving part. Each of the materials used for slip rings and commutators, such as iron, steel, bronze, and copper, gives a different coefficient on the same brush. In the case of brush composition, friction increases with the hardness and the amount of abrasive, and decreases with increase of graphite and with the addition of other lubricant. Metal-carbon brushes have more friction than plain graphite and about the same as the harder carbon brushes, the friction increasing with the percentage of metal in the brush. Slip ring friction is assumed to be the greatest for cast iron and least for copper, values for the metals generally used decreasing in the following order: cast iron, steel, bronze, brass and copper.

Friction is lowest when brushes are mounted at an obtuse angle with the approaching surface of the rotating part. It is greatest when they are mounted at an acute angle with this approaching surface. Some of this effect is due to the contact of the brush with the walls of brush holder when the box type is used.

Friction is greater when the surface of the rotating part is rough and less when it is well polished. Increasing peripheral speed decreases the coefficient of friction, and friction generally increases with brush pressure.

V. In the preparation of formulas and curves for the use of the designer we must consider the six variables presented under section IV, as they all affect the value of the friction coefficient. A series of diagrams is proposed, one for each brand of brushes. These diagrams should have separate curves for the various pressures to which the brush is adapted such as the set of curves for one brand shown in Fig. 8; they should show the variation in coefficient due to change in peripheral speed, and they should give the factors used in modifying coefficients to agree with angle of brush, material and surface condition of rotating part.

With a dependable value for the coefficient of friction the power consumption expressed in watts may be calculated, using the formula:

$$\text{watts consumed} = 0.0226\, P\, A\, V\, K$$

in which 0.0226 represents the ratio $\frac{746}{33000}$

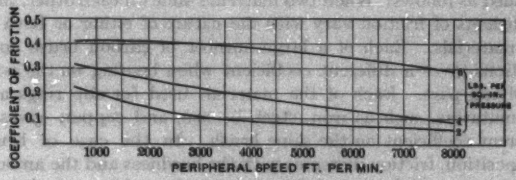


FIG. 8

P = normal brush pressure in lb. per sq. in.,
A = total contact area of brushes in sq. in.
V = peripheral speed of rotating part in ft. per min., and
K = coefficient of friction (adjusted to suit conditions).

In this connection it is interesting to note that a great many formulas are extant, mostly empirical, for determining watts input. Eight of these now in use were applied to a concrete case, with results varying from 910 to 3450 watts. It is likely that the tolerance of these widely varying formulas is explained on the ground that they will all check with actual tests depending on the operating conditions existing at the time of the test.

It is possible that other values might be profitably substituted for "Coefficient of friction," in Fig. 8. For example,

" watts consumed per pound pressure per inch diameter of rotating part " would put the values into convenient form for use on the testing floor.

Because of the limited time for making tests, the actual friction coefficients for the principal types of brushes cannot be presented in this paper. A complete statement of these figures may be expected at a later date.

General Conclusions

In discussing brush losses due to contact and friction we have done little more than indicate the avenues along which investigation should proceed and the nature of the results which will be useful to designing engineers. Some troublesome variables have been pointed out, the controlling of which should materially increase the accuracy of results.

Because of the complexity of these tests and the length of time and expense of apparatus necessary to produce dependable results it may be argued that commercial tests, those made on machines actually in course of manufacture and awaiting shipment, should be sufficient to give all necessary information. Our experience in attempting to correlate results of such tests and establish laws therefrom has been exceedingly discouraging, and we are convinced that improvements in the design of electrical apparatus as related to brushes and in the quality of the brushes themselves must result from the establishment of more accurate values for the losses due to brush contact and friction.

There is also every reason to believe that accurate values thus established will be found so much more reliable than actual performance tests that they will be substituted for such tests in the majority of cases.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 27, 1913.

Copyright, 1913. By A. I. E. E.

COMMUTATION AND BRUSH LOSS

BY C. E. WILSON

Even when made on slip rings, or on special short-circuited commutators, brush loss tests are hard to duplicate and results of tests under similar conditions vary greatly. A number of things are known to affect the brush loss at a given current density. Among these, the most important are: the direction of current in the brushes, the glaze or polish of the collector, the surface and fit of the brushes, oil or any foreign material on the collector, the temperature of the parts and the peripheral speed of the collector.

In direct-current machines, there are still other reasons for variations in brush loss. It is likely to be increased by high mica, unequal division of current among the brushes and brush arms, vibration or chattering of the brushes, imperfect spacing of them, and, above all, by the commutation and the strength of the magnetic fields in which the short-circuited coils are commutated. In fact, tests show that one machine may have two or three times the brush drop of another of the same type, although the grade of brushes and the apparent current density in them are the same. Even in the same machine, with the same current output, the brush drop measured at the different brush arms and at different times, may vary 100 per cent or more.

Table I gives the tests on four adjustable-speed motors of the same type, at the maximum and minimum speeds for which they were designed. These were chosen at random from a large number of tests made on this line of machines, all of which were equipped with the same grade of brushes.

The voltages A, B and C were taken at different points on the brush and commutator, as shown in Fig. 1, and were measured

TABLE I

TESTED BRUSH DROPS ON ADJUSTABLE SPEED MOTORS

Rating			20 amperes per sq. in.						40 amperes per sq.in.						60 amperes per sq. in.					
			Volts *A*		Volts *B*		Volts *C*		Volts *A*		Volts *B*		Volts *C*		Volts *A*		Volts *B*		Volts *C*	
H.p.	Volts	Rev. per min.	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−
20	115	300	1.1	0.9	0.7	0.7	0.8	0.7	1.5	1.3	1.1	0.9	1.5	1.2	2.2	1.3	1.6	1.2	2.2	1.0
		1200	1.3	1.5	0.5	0.6	−0.5	0.0	1.6	1.8	1.1	0.9	0.7	0.9	1.4	0.7	1.3	1.0	1.8	1.7
25	230	300	0.9	0.6	0.7	0.6	0.4	0.7	0.9	0.7	0.5	0.9	0.1	1.3	0.7	1.8	1.1	1.1	1.7	2.1
		1200	0.4	0.4	0.3	0.3	−0.1	−0.1	0.5	0.4	0.5	0.5	0.3	0.7	0.5	0.6	1.0	1.3	2.3	2.2
25	115	400	0.4	0.5	0.5	0.1	0.3	0.2	0.6	0.9	0.7	0.2	0.6	0.3	0.8	0.8	0.7	0.3	0.8	0.6
		1200	0.9	1.00	0.5	0.5	0.2	0.1	1.1	1.1	0.7	0.7	0.5	0.5	0.7	1.2	0.9	0.9	0.7	1.0
30	230	350	0.3	0.4	0.1	0.3	0.0	0.2	0.4	1.4	0.2	0.9	0.1	0.7	0.3	1.3	0.2	1.0	0.5	1.2
		1050	0.6	0.5	0.1	0.1	−0.6	−0.5	0.5	0.7	0.1	0.2	−0.3	−0.3	0.4	0.6	0.2	0.3	0.1	0.2

in the usual way with a low-reading direct-current voltmeter and a pair of pencil points making contact at 1-1, 2-2 and 3-3, as shown. The current densities given correspond to approximately one-half, full load and 50 per cent overload on the motors.

The data recorded in Table I show, principally, the extreme variations in brush drop found in commercial testing. These variations can usually be explained by one of the causes previously given. The overshadowing influence of the commutation and the commutating field on the brush drop is also shown clearly. As far as measuring the loss is concerned, the product of the average brush drop and the load current is such a rough approximation that it is often practically worthless. In some cases the loss obtained in this way is less than the loss measured on slip rings and short-circuited commutators. It is hard to see how this can

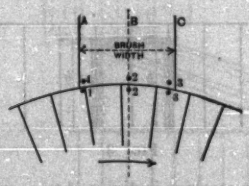


FIG. 1

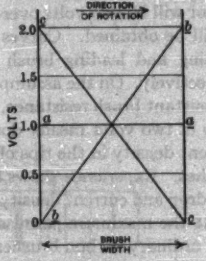


FIG. 2

possibly be true, as all the things which affect the loss in machines tend to increase it.

It should be remembered that the primary function of a brush is to commutate and collect current. Brushes are selected for their commutating qualities, primarily, and the brush loss is of secondary importance. The commutation is first made right and then the question of loss is considered. A machine which has a high short-circuit or reactance voltage demands a high-resistance brush, especially in the case of a machine without compensating windings.

In the case of an ordinary commutating pole motor, a reasonable value for the total inherent short-circuit voltage* across the

* Figured according to the method given in Mr. B. G. Lamme's paper, *A Theory of Commutation and its Application to Commutating Pole Machines*, TRANS., A. I. E. E., 1911, Vol. XXX, p. 2359.

brush at full load, is 15 volts. Assume that, in order to neutralize this voltage, the ampere-turns on the commutating pole must be 30 per cent in excess of the armature ampere-turns, or a total of 130 per cent. With this value of ampere-turns, and with a commutating field of the proper shape, the theoretical curve *a* in Fig. 2 will be obtained. If the ampere-turns on the commutating pole are decreased to 126 per cent of the armature ampere-turns, the neutralizing voltage will be decreased to 13 volts and the motor will be two volts under-compensated, and a brush curve such as *b* in Fig. 2 will be obtained. A local current will then flow in at one brush tip and out at the other. This curve assumes constant brush resistance. However, the actual curves approximate these theoretical ones with sufficient accuracy for purposes of illustration. If the ampere-turns on the commutating pole should be increased to 134 per cent of the armature ampere-turns, the motor will be two volts over-compensated, and curve *c* in Figure 2 will be obtained. Curves *b* and *c* show two volts drop at the trailing and leading brush tips respectively. On the assumption of constant brush resistance, this drop of two volts means double current density in the tips of the brushes. Experience shows that this drop and current density are about the maximum permissible with ordinary carbon brushes, if the machine is designed to carry a reasonable overload with perfect commutation.

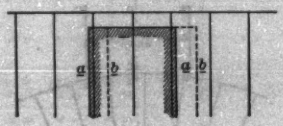


FIG. 3

To obtain this desirable adjustment in such a machine, the commutating pole ampere-turns must be correct to four parts in 130, or within approximately 3 per cent. If, for any reason, the effective ampere-turns on the commutating pole vary independently of the armature ampere-turns in excess of 3 per cent, commutation trouble is likely to be experienced.

The voltage across the brush is usually measured with a direct-current voltmeter. If an alternating-current meter which would read correctly on high frequency were used, an entirely different reading would be obtained in the majority of cases. This is due to the variation in the short-circuit voltage which occurs during the period of commutating one bar, and in some cases, during the commutation of the bars on one slot. This variation in short-circuit or reactance voltage cannot be correctly compensated by a commutating pole which will only give the proper

average values. It is quite apparent that a different condition is encountered when the brush is in position *a* than when in position *b* in Figure 3; likewise, when the brush passes from bar *a* to bar *b* and from bar *b* to bar *c* in Fig. 4. This is one of the reasons why the brush drop, as measured on machines, is so variable that tested values are practically meaningless and worthless so far as measuring the loss is concerned.

In the case of a non-commutating pole machine, it is still more necessary to have a high-resistance brush if the short-circuit voltage is high. It is common practise to shift the brushes of a non-commutating pole machine from the mechanical neutral, in order to induce a voltage in the short-circuited coils, due to the main field which will neutralize the short-circuit voltage. A fair limit for the short-circuit voltage across the brush of a non-

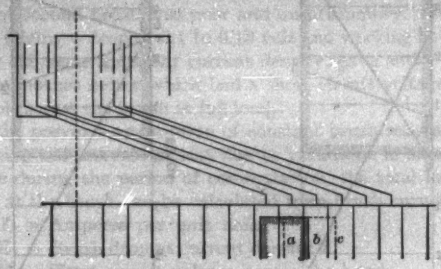


FIG. 4

commutating pole machine at full load is six volts. Assuming high-resistance carbon brushes with constant brush resistance and a drop of 1¼ volts at a nominal current density of 35 to 40 amperes per square inch (6.45 sq. cm.), the brushes may be shifted into an active field which will give five volts at no-load, and a current density in the brush tips of twice the normal value. A brush curve similar to *a* in Fig. 5 will then be obtained. At full load, this five volts will neutralize all but one volt of the short-circuit voltage and curve *b* will be obtained. At 50 per cent overload, curve *c* would be obtained with approximately three times current density in the trailing brush tip and the condition of poor commutation. The probable limit for commutation on such a machine would be 25 per cent overload. The brush loss in this machine at no-load would be considerable, and this is

often found to be the case, as shown by tests. Often the no-load losses are decreased much more by raising the brushes than can be accounted for by the decrease in loss due to the absence of brush friction. Many tests have been made to measure this no-load brush loss, and it has been found to be comparatively large. In the case of curve *c* at 50 per cent overload, Fig. 5, the loss in the tip of the brush would be approximately nine times normal, and would undoubtedly cause glowing and honey-combing of the brushes.

The commutation of non-commutating pole direct-current machines has often been improved by narrowing the brushes and

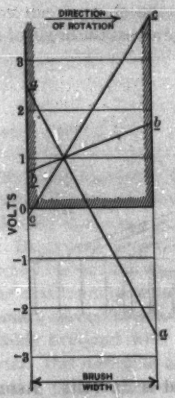


FIG. 5

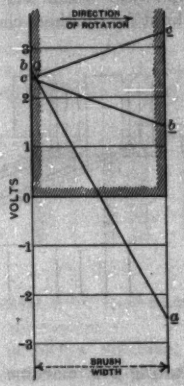


FIG. 6

increasing the apparent current density in them. For example, consider the brush in Fig. 6 to be reduced from ¾ in. (18.9 mm.) to ½ in. (12.7 mm.). The short-circuit voltage at full load will then be approximately four volts, and curves *a*, *b* and *c*, Fig. 6, will be obtained at no-load, full load and 50 per cent overload respectively. With this narrower brush the loss in the tips of the brushes is the same as before, but the total loss is less, because the section of the brush has been reduced. The loss at full load is practically the same as before, but the loss at 50 per cent overload has been reduced so that commutation might be satisfactory. Actually the improvement is greater than indicated, due to the

fact that the brush does not have a constant resistance, but has a resistance which decreases with increase in current density.

The writer recently had this relation between brush drop and the commutating characteristics of a machine forcibly illustrated by his experience with a line of small six-volt motors. In order to improve the efficiency, very low resistance brushes were used. In a given case, the short-circuit voltage was 0.75 volt across the brush at full load. The commutation was perfect with brushes having a nominal brush drop of 0.25 to 0.3 volt at a current density given by full load on the motor. To improve the efficiency, other brushes were tried having a drop of 0.1 to 0.15 at this same current density. The efficiency by brake was practically the same for both cases, showing that the low-resistance brush had not decreased the total brush loss. Also, the commutation with the second brush was poor and unsatisfactory. This same brush, having a drop of 0.1 to 0.15 volt and working at approximately the same apparent current density, gave entire satisfaction on another motor which had a short-circuit voltage of only 0.35 volt across the brush at full load.

On the previous assumption of constant brush resistance, and neglecting the increase in loss due to variations in short-circuit voltage during the period of commutation, the total loss which occurs at the brush can be calculated from brush curves.

Let I_1 = Amperes per unit area.
E_1 = Brush drop at current density I.
E_2 = Short-circuit voltage across the brush.
A = Area of brushes.

Then the brush loss on a short-circuited commutator would be

$$W = E_1 I_1 A$$

When a local current, caused by the short-circuit voltage E_2, is present in addition to the useful current, the loss can be shown to be

$$W_l = E_1 I_1 A\left(\frac{4 E_1^2 + \frac{1}{3} E_2^2}{4 E_1^2}\right) \text{ or, if}$$

$$a = \frac{E_2}{E_1},\ W_l = E_1 I_1 A \left(\frac{12 + a^2}{12}\right) \text{ and the increase}$$

in loss will be $8\frac{1}{3}\, a^2$ per cent.

Referring to curves *b* and *c* in Fig. 2, the increase in loss due to the local currents caused by the two volts across the brush will be 33⅓ per cent. Actually the increase in loss with such a brush curve as *b* or *c* will be considerably more than 33⅓ per cent, due to the decreasing brush resistance with increasing current, as previously mentioned. This decreasing brush resistance allows a larger local current to flow, which, of course, increases the loss.

Referring to curve *a* in Fig. 5, the brush loss at no-load would be 133⅓ per cent of the loss at normal full-load current density and no local currents.

There appears to be no way of measuring this increase in brush loss, or, as it may be called, commutation loss. In the average commutating pole machine, this increase in loss probably does not exceed 50 per cent, but it may be very much greater in some cases. Probably the most satisfactory method of dealing with this total brush loss is to obtain a value for what may be called the true brush loss from data obtained by tests on short-circuited commutators, and to regard any increase in loss which may occur, as commutation loss or part of the load losses.

GROUP II PAPERS

(Pages 423 to 584)

Method of Determining Losses in Apparatus

(a) INDUCTION MOTORS

Induction Motor Load Losses, by H. G. Reist and A. E. Averrett.
Stray Losses in Induction Motors, by A. M. Dudley.
Notes on Induction Motor Losses, by R. W. Davis.

(b) TRANSFORMERS

Losses in Transformers, by W. W. Lewis.
Stray Losses in Transformers, by C. Fortescue and W. M. McConahey.

(c) GENERATORS, A-C. AND D-C.

Determination of Load Loss Correction Factors for Rotating Electric Machines, by E. M. Olin and S. L. Henderson.
Load Losses of Alternating-Current Generators, by W. J. Foster and E. Knowlton.
Notes on Stray Losses in Synchronous Machines, by F. K. Brainard.
Stray Loss in Direct-Current Commutating Machines, by H. F. T. Erben and H. S. Page.

(d) ERRORS OF TESTS

The Determination of Stray Losses from Input-Output Tests, by L. T. Robinson.
Sources of Error in the Efficiency Determination of Rotating Electric Machines, by Elmer I. Chute and William Bradshaw.

(e) BRUSH LOSSES

Brush Friction and Contact Losses, by H. F. T. Erben and A. H. Freeman.
Methods of Determining Brush Losses Due to Contact and Friction, by H. R. Edgecomb and W. A. Dick.
Commutation and Brush Losses, by C. E. Wilson.

Discussion on Group II Papers (Methods of Determining Losses in Apparatus), New York, February 27, 1913.

(a) Induction Motors

A. E. Averrett: Regarding the separation of copper losses, there seems to be a tendency on the part of some users to want bar-wound stators on account of the ease of repair. You can make a bar-wound stator with rather deep bars, but if you have a rotor that is bar-wound also and assume that the losses are practically all in the rotor, these will disappear at synchronous speed and you will apparently have a more efficient machine than you really have, if all the losses are taken into consideration. But you can actually get the loss by taking out the rotor and measuring the impedance of the stator alone by wattmeters, which will show up the losses correctly if the tests are made carefully.

It seems to me that the present method of summation of losses will apply only where the impedance-ampere curve is a straight line proportional to voltage (which shows no saturation in the iron) and where there are no eddy losses in the stator copper, which can be shown up by the wattmeter measurement at impedance. There is one feature about a deep rotor bar where we neglect the losses; there is a reduction in power factor due to skin effect in deep rotor bars which does not show at standstill test.

B. A. Behrend: I want to make a plea for the adoption of the term "stray losses" instead of the term "load losses" or losses incidental to operation. We understand by "load losses," as the term is used, a great many losses, including certain losses which occur at no-load, losses which occur in certain cases at full load, and losses which occur at both no-load and full load, and I think the adoption of the term "stray losses" would be a little more logical. We have a certain stray loss at no-load, we have a certain stray loss at full load, and instead of the use of the term "load loss," which is used in some of these papers as a loss occurring at no-load, I think we should use the term "stray loss." I believe that Mr. Hobart, who suggested my making these remarks, agrees with the substitution.

C. P. Steinmetz: We are particularly interested in the magnitude of the additional stray losses which we have at load, and we are only in a less measure interested in the stray losses at no-load. These latter need rarely be segregated from the total losses at no-load. We need a satisfactory name for those losses which appear at load, and are not accounted for by the usual methods of measuring individual losses. "Load loss" is rather a poor name, because there are many other losses which are accounted for in a separate test; but "stray loss" does not cover it exactly either, and we should have some additional name.

James Burke: Following Dr. Steinmetz's remarks, would it be consistent to speak of "stray no-load losses" and "stray load losses?" We have both kinds of stray losses. These papers show that in some kinds of motors the stray load losses may be very considerable. In other types they may be very small. Generally, the reduction in core losses due to the drop in the stator windings, resulting in lower total magnetization, compensates for the usual load stray losses, so that there is not very much to be taken into consideration if the free core losses are used rather than the corrected core losses after the reduction in the magnetism in the machine. It would seem, however, that in formulating any new rules, we must take proper recognition of the stray load losses, because from these papers it is evident that we may have very considerable stray load losses, or they may be negligible, and that fact would seem to make it necessary to formulate some plan by which they would be properly taken into consideration when they exist.

H. M. Hobart: We ought to have four components in this proposition. The four components I have in mind are: first, output; second, no-load loss; third, the load loss (by which we mean the legitimate load loss), increasing as the square of the current; and fourth, what we might call "stray losses," that is, the losses which, at full load, we must add to these other three losses in order to get the input at full load. This fourth part, which we have been apt to ignore in the past, and which we shall probably have to take into account in the future, could be given the name "stray losses," instead of, as in some of the papers, being termed "load losses." I should prefer to reserve the term "load losses" for what we call the legitimate losses coming on with the load.

Leo Schuler: Does Mr. Hobart propose to call losses due to distortion of the field, stray losses as well? They certainly are not stray losses.

H. M. Hobart: For practical purposes I should have input, minus output, minus no-load losses, minus I^2R losses, coming on with the load, which I should call stray losses.

Leo Schuler: You then include losses which are not stray losses.

Perhaps it will interest you if I say that in Germany we have the no-load losses, which include also stray losses if there are any, and then speak of "additional losses" simply. Additional loss means the loss which does not come on at full load, and which is not accounted for by what you call the load losses.

B. G. Lamme: Stray losses?

Leo Schuler: As far as I understand, load loss is better than stray loss.

H. M. Hobart: I do not care what it is called, if we do not confuse it with other losses. "Extra losses" would be a good term.

B. A. Behrend: The objection is to the use of the term "load loss." It is not implied that the expression "stray" is such

a general term, but it might be as good a one as any other. An objection to using the term "load losses" is that in an equivalent test it might mean legitimate losses or extra losses.

B. G. Lamme: The term "load loss," as Mr. Behrend says, is a very misleading one, because practically all our secondary copper loss is a load loss. Practically all of our primary copper losses are load losses, and when we speak of load losses we should include all these, and yet what we are after is the additional extra loss which we call the "stray loss." I do not think, whatever other term we use, that we can dispense with the use of that term—after we have described our "load losses," we will still have use for that term "stray losses," or some other similar term.

A. E. Averrett: I believe load losses are included in the legitimate copper losses and legitimate iron losses, plus excess losses. On induction motors, these losses occur only on the load running light. There is no excess loss.

R. E. Hellmund: The present Institute rules are not quite right, in so far as they give the losses in too general a way. These papers give suggestions as to the method of determining the losses for practically all cases, with the possible exception of machines with entirely closed slots. As has been said, such cases are comparatively rare. All other cases can be taken care of, if the Committee would adopt the suggestions made in the paper of Messrs. Reist and Averrett, and the paper of Mr. Dudley.

It might appear at first sight that Mr. Dudley's suggestion of finding the true I^2R loss by testing the motors for different frequencies is impracticable, but it must be considered that almost any factory has generators available with at least two or three frequencies. Since the method is on the other hand the only method proposed for finding the I^2R losses in large squirrel-cage motors, I would advocate that the Institute adopt this method as one of its standard methods.

C. J. Fechheimer: Messrs. Reist and Averrett make the following statement: "Tests have been made which verify the above statements; round wires or rectangular strips of one cm. or less for a maximum dimension, apparently do not show any appreciable loss." This refers to eddy current losses in copper conductors. I would call attention to the fact that eddy currents are a function of the frequency and increase very rapidly with an increase in frequency. At standard frequencies the loss is negligible with the depth of conductor given, but it would be possible to raise the frequency high enough to cause a very large eddy loss with the same size conductor.

We believe that the method which is mentioned briefly at the end of this same paper, that is, of obtaining the losses at various frequencies, would be the proper one to determine the extent of the eddy losses. If we go down low enough with the impressed frequency the eddy current loss becomes negligible

and we then have a direct means of measuring these losses with accuracy.

R. E. Hellmund: We first have to find out what the extra losses are at standstill and then separate them. Mr. Dudley proposes to find out what they are by measuring at different frequencies and then separating them, either by the rule of making them proportional to the square of the depth of the conductor, or by taking the rotor out of the stator and testing the stator separately.

There are two steps to be taken, and I think they are very proper steps, in large machines, where it is not possible to get the secondary losses by slip readings. In smaller machines I think the method proposed by the first paper is very desirable, that is, to get the secondary losses by slip readings and the primary losses by considering the I^2R losses, or, in the case of heavy conductors, by making the additional test of the stator without the rotor.

Comfort A. Adams: I want to say a word in favor of the German name translated as "additional losses". The term "stray losses" has been for many years much used to represent the no-load losses, that is, the friction and windage losses, and losses measured when the machine is running absolutely light. Thus in order to avoid confusion it seems to me that "additional losses," a perfectly distinct name, would be more appropriate. Referring to Mr. Fechheimer's question as to iron slot bridges and the reduction of the total flux at full load, it is obvious that if you mean by total flux the useful working flux, plus the leakage flux, it is practically constant at constant impressed voltage, differing therefrom by only the IR drop, which is small. But the part of this total flux which is increased by the bridges, namely, the leakage flux, is in a magnetic circuit of relatively short length, and involves a much smaller volume of iron, although at much higher density. It is thus impossible to say, definitely, whether the bridges would increase or decrease the total core losses.

James Burke: I want to answer Professor Adams's point regarding the difference in core losses. Very often on motors below 10 h.p. there is a 5 per cent reduction of e.m.f. due to 5 per cent drop, which makes about 5 per cent difference in core loss. On larger motors this is much less, but in motors of 10 h.p. or less a large IR drop in the stator generally exists.

Comfort A. Adams: Mr. Burke's statement is undoubtedly correct, but if the resistance drop is constant for any given load, say full load, the effect of the slot bridges is not to change the total flux, but to increase the leakage flux at the expense of the main flux, as above described.

B. A. Behrend: It seems to me extremely dangerous to draw an inference from the excess over an assumed rate of increase. We are familiar with the fact that the core loss in induction motors rises at a greater rate than the square of the

impressed voltage, and, therefore, any inference based on the law of increase as suggested, would be, to borrow a phrase used by Mr. Burke, "mind reading" rather than good engineering.

A method of that sort seems most dangerous to me, and in this connection I wish to second the remarks made by Mr. Schüler and Professor Adams on the use of the term "indeterminate losses." It seems from the discussion that the use of the term "indeterminate" would be excellent, because no one knows how to determine them.

C. P. Steinmetz: In connection with Mr. Behrend's remarks, I wish to say that I have never seen any core losses go up faster than the square of the voltage, or even as fast as the square of the voltage, except in those cases where there was saturation somewhere. Practically any core loss, if you run the voltage high enough, will begin to rise abruptly at the point where saturation is reached, and then the increase goes up according to powers ranging from the square to the cube and sometimes even at still greater rates. The abrupt increase of core losses beyond the quadratic rate at high voltages is an indication that saturation is the cause.

In view of the general experience with core losses in commutating machines, and in motors, especially in the commutating induction motor, we must expect that as soon as saturation is passed anywhere, we will have an abnormal rise of core loss, but below saturation the core loss does not go up as the square.

B. A. Behrend: I do not question the approximate truth of the 1.6th power law of Dr. Steinmetz's—but this is not a practical condition obtaining in any generators or motors, and therefore the core loss does increase more rapidly than the 1.6th power or even the square, at high inductions.

C. J. Fechheimer: I plotted a number of core loss curves on generators far below the saturation point, plotted them on logarithmic paper to determine the exponent, and I found in a number of cases that the exponent was higher than 2. There were a couple of cases below 2, but the general average was around 2, below saturation, and I have never been able to account for it.

Comfort A. Adams: The reason why the core losses behave so erratically in the case of induction motors is that they are not losses which occur, as in transformers, under conditions of fairly uniform density and single frequency. There are at least five different kinds of core losses in an induction motor, or five ways in which they occur, so that if the calculations could be made it would require five separate calculations. There are losses at fundamental frequency behind the teeth, at fundamental frequency in the teeth, at tooth frequency in the teeth, at tooth frequency in certain portions of the core back of the teeth, due to the tooth and slot groupings on the two sides of the gap, wave losses in the faces of the teeth, and, finally, illegitimate losses due to the breakdown

of the insulation between laminations. It is thus not a simple matter to compute these losses, and not strange that they do not behave according to the manner of the core losses of well-behaved transformers. The increase more rapid than the square of the voltage is due partly to the wave losses in tooth faces and partly to a progressive breakdown of lamination insulation as the eddy e.m.fs. increase.

B. G. Lamme: In some cases the so-called iron losses increase very rapidly with the load, and also very rapidly with the induction. I have found many cases in which an abnormal increase in apparent iron loss occurs with only slightly increased inductions. But in many of these cases, if the copper was removed from the slots, the loss did not go up nearly so fast; that is, the so-called iron loss was, in reality, largely eddy current loss. The confusion comes from the fact that where iron losses are referred to, in most cases the term "core loss" should really be used. Part of the extra losses found may be true iron losses, but are eddy currents in the iron due to burred edges of the laminations in the slot, due to filing, etc.; they also may be due to contact between the plates. Such losses, if located in the armature teeth, may go up much more rapidly than the square of the induction, for they may be a function of the tooth saturation. I have found cases where the loss went up to as high as the 5th power of the induction, but this was largely eddy current loss in the teeth and armature copper, which is dependent upon the degree of saturation of the armature teeth. In fact, therefore, before arriving at any conclusions regarding the variation of the iron losses with the voltage, we should first find what really is iron loss and what is something else.

R. B. Williamson: Mr. Lamme has mentioned the paper by Mr. Field on eddy currents, in which the eddy current losses in conductors were shown to be due to the cross flux in the slot. In slots that have been filed or drifted, the laminations become more or less connected together, and the cross flux may set up considerable loss in the side walls of the teeth. A machine that shows high core loss on open circuit will, in many cases, also show a high short-circuit loss; that is, there is a connection between the two, and I believe a great deal of this loss is due to eddy currents in the teeth, or in the side walls of the teeth.

B. A. Behrend: As to the discrepancies in the opinions expressed by Dr. Steinmetz and myself, let me say that core losses are not iron losses, as I have used the term, and as I believe most of us are using it. Core losses also contain indeterminate losses. The iron loss is one thing, the copper loss is another, and the core loss may contain copper losses and iron losses and losses due to the filing of cores and bad workmanship, as well as losses due to stray fields from magnetic fields in the end plates or anywhere in the machines. I think that as we measure core losses, and not iron losses, it is not rational to talk of iron losses,

except in calculations. This seems to me, from twenty years of experience, a matter of course, but I felt constrained to point it out, as the iron losses, if they could be separated and isolated, would not increase at a rate greater than the square of the induction. The core losses, however, do show such increase.

C. P. Steinmetz: I would say that transformers and induction motors for 60-cycle circuits, are two classes of apparatus in which good practise keeps the magnetic densities below saturation, or certainly does not let them go beyond saturation. Consequently, changes in voltage are not associated with changes in the flux path. As long as there is no change of flux path, all the losses must be dependent on the voltage or the current. The eddy losses would change with the square, the iron losses probably less than the square, so that the combined effect cannot exceed the square of the voltage, except where, by saturation, the flux path is affected.

B. A. Behrend: I believe there are about three million h.p. of induction motors in operation, with the design of which I have been concerned in one form or another, and I believe almost all of these induction motors carried the saturation above the bend of the saturation curve in the teeth of the rotor, and also in parts of the stator, and I am a little at a loss to understand the remarks of Dr. Steinmetz in this connection, because saturation is almost invariably used in the teeth of the rotors of induction motors, and not infrequently in other parts of the magnetic circuit.

C. P. Steinmetz: I think the confusion exists in the indefinite meaning of the term saturation. I mean such densities of saturation that the m.m.f. consumed in the iron is of the same order of magnitude per unit of length of the magnetic circuit as the m.m.f. consumed in the air gap. That, naturally, would not be desirable. Exceeding the bend of the saturation curve is really not yet saturation, in the meaning of the term as I have used it. You can go beyond that for a little way and still not seriously increase the proportionality between the exciting current and the voltage.

H. M. Hobart: Another circumstance, as showing our ignorance of this subject, could be mentioned. If in the laboratory you measure the specific resistances of two samples of iron, one of high and the other of low specific resistance, the eddy current loss may be as great in the one with high specific resistance as in the one with low specific resistance. Pending an explanation of this, we must admit that we do not know much about eddy current losses.

L. T. Robinson: We do not know very much about these things. An encouraging sign is that we begin to take an interest in them, with the object and hope of finding out more about them.

R. E. Hellmund: It has been brought out that the core losses, as a rule, rise with the square of the voltage impressed

on induction motors, more so than in the case of transformers. That is partly due to high densities in certain parts, but I take it that most of it is due to the fact that the largest part of the losses in induction motors, of practical design, are eddy current losses, and only the smallest proportion of the losses are hysteresis losses. In considering transformer iron, with about 60 cycles, the hysteresis loss is pretty large as compared to the eddy loss. In the case of the induction motors the hysteresis losses are in many motors only about 20 per cent, while all the rest of the losses are eddy current losses, caused by the higher frequencies in the teeth. Now, as we all know, the eddy losses go up with the square of the voltage, and since the eddy losses in most motors are more than half of the total losses, it is not surprising that the curve follows the law of the eddy loss rather than that of the hysteresis losses. It is therefore really not surprising that the core loss curve is nearly the curve of the squares, even for low densities.

B. A. Behrend: Once more to the subject of saturation, and the iron losses, where hysteresis alone may be considered. Dr. Ewing, who first brought out the general principles of induction in iron and other metals, suggested to Professor Baily of London certain physical research work, the results of which are published in the *Transactions* of the Royal Society. The paper of Professor Baily is fundamental, and he proves that rotative hysteresis diminishes at high induction. With the induction plotted as an ordinate and the loss plotted as an abscissa, Professor Baily's researches show that at saturation, viz., $4\pi I$ in the relation $\mathbf{B} = \mathbf{H} + 4\pi I$ having become a constant, the loss diminishes. Whatever induction we have below or beyond that point is the induction, **B,** which is the sum of the air field plus the iron field. This was experimentally demonstrated in Professor Baily's paper. I also carried on some experiments in our own laboratories about eight or ten years ago, and I found an approximation to a similar result. We eliminated eddy currents as nearly as possible, and we found that the loss diminished at high inductions.

M. G. Lloyd: Mr. Behrend is quite right in his reference to the experiment of Professor Baily, and further work along the same line has been done by others, especially by Professor Weiss, of Zürich. The curve between watt loss and magnetic flux density has been found to come down almost to zero at sufficiently high values of the flux density, but this applies only to a case where you have a purely rotary magnetic field, constant in intensity and simply changing its direction in the magnetic material. I do not believe that such a condition can be found in any kind of a machine such as an induction motor. You always have there a combination of a rotary effect with a reversing effect, that is, you have pulsation of the magnetic field in both time and space. In a case like that the law illustrated by Mr. Behrend's curve no longer holds.

H. M. Hobart: In view of our demonstrated ignorance in these matters of hysteresis and eddy current losses, we must base our reasoning on the results of tests, and we should refrain from basing any conclusions on deductions from old-fashioned conventional alleged truths which have been shown to be not only inadequate but utterly misleading.

R. E. Hellmund: In considering the field distribution in induction motors, we must not only consider the effect of the primary, but also the effect of the secondary. The secondary, if short-circuited, has a correcting effect upon the field. This is especially the case in squirrel cage motors. For instance, a squirrel cage rotor with an infinite number of bars will always correct the field so it will have a sinusoidal distribution, no matter what the initial distribution of the field as set up by the primary winding. In actual practise, the correcting effect of the secondary with a limited number of slots, will be such as to cause the field distribution to be very nearly sinusoidal. We must therefore say that the chording of the primary has little influence upon the actual field distribution, but that it will have a big influence upon the correcting currents in the secondary.

In other words, we may say that the correcting secondary currents and the losses caused thereby are the smaller, the more the initial field set up by the primary approaches a sinusoidal field.

The initial primary field in three-phase motors with full pitch is not quite ideal in this respect. By introducing a chording sufficient to have two of the phases overlap half-way, we obtain an almost sinusoidal primary field distribution. By chording the coils considerably more than that, the field becomes worse again and will be the same as in the case of full pitch, if two of the phases overlap entirely. In two-phase motors, the initial primary field with full pitch windings is considerably worse than in three-phase motors, but also in this case phases overlapped about one-half improve the initial primary field considerably.

It follows from the above that while the chording of the winding has no great influence upon the actual field distribution, it is, if properly chosen, an advantage with regard to the operation of the motor.

James Burke: That also happens in the loaded conditions?

R. E. Hellmund: It is pretty hard to say just exactly what happens in the loaded condition, but my previous statements certainly do apply to the synchronous condition.

Comfort A. Adams: Mr. Hellmund's statements are quite in line with my ideas in this matter, but he undoubtedly assumed one condition, which he did not mention; that is, that the correcting effect of the secondary is only complete under the assumption of zero resistance and reactance in the secondary.

R. E. Hellmund: Yes, this assumption has to be made in order to get ideal correcting effect.

Comfort A. Adams: In most squirrel cage motors this condition is, of course, nearly fulfilled. If you had zero resistance and reactance, evenly distributed, it would wipe out all kinds, no matter what the e.m.f. condition was. As you reduce the coil pitch below two-thirds in a three-phase motor, say to 50 per cent, you might assume that there would result the same perfect m.m.f. distribution as for $\frac{2}{3}$ pitch, but this is not so, because the currents in the overlapping phases have larger phase differences and yield quite different amplitudes in adjacent belts. The phase differences of the resultant currents in the various belts and the number of belts (12) is the same as for $\frac{2}{3}$ pitch, but when you go down to 50 per cent pitch, you may have what Mr. Lamme has indicated, an actual local reversal of the flux.

(*b*) Transformers

J. M. Weed: The two papers on transformer losses are in a sense complementary to each other, but after both papers are read, there are some discrepancies apparent which need to be harmonized, and some points which still need to be brought out to clear up the subject.

The paper by Messrs. Fortescue and McConahey mentions the losses due to eddy currents in the copper, and those due to circulating or unbalanced currents in unsymmetrical parallel windings, but dismisses them with the statement that they are negligible in careful designs. In the remaining part of the paper these losses are ignored, the total copper loss being classified as I^2R loss and stray loss (see section V of the paper). The term stray loss is confined to that part of the loss in the primary winding due to the resultant of load current and exciting current which is in excess of that which would be caused by the load current alone plus that which is caused by exciting current alone. In equation (**24**) the term "short-circuit loss" is used as an alternative term for I^2R loss, and is intended to refer to the loss which would be caused by load current alone.

On the other hand, Mr. Lewis calls the loss due to the resultant of load and exciting currents the I^2R loss, and classifies the extra losses due to magnetic leakage, which include the losses due to eddy currents, as stray loss. Moreover, the extensive tabulations of tests given by Mr. Lewis show that these losses are often far from negligible, varying as they do from a small value to more than 50 per cent of the I^2R loss.

This discrepancy in the use of terms is no doubt the result of efforts on the parts of the authors of both papers to use in a rational and discriminating way the old stereotyped terms "load losses" and "stray losses," which have been used rather indiscriminately to cover a multitude of sins. This effort has taken different directions in the two cases.

Messrs. Fortescue and McConahey have confined the term "stray loss" to a rational significance, that of a loss which escapes measurement. This applies to the extra loss due

to combining the load and exciting currents, but not to the losses due to magnetic leakage.

On the other hand, Mr. Lewis has made the term "load loss" to include the I^2R loss, which, in so far as it is due to load current, certainly is a load loss. But he has made the I^2R loss of the primary to include the total loss due to the resultant of exciting current and load current. This loss all might properly be called I^2R loss, but not all load loss, since that element of it due to exciting current alone is included in the open-circuit or "no-load loss."

Probably the losses which Mr. Lewis has designated as stray loss would be more properly designated as losses due to magnetic leakage, or extra losses due to loading, these losses being included with the I^2R losses due to loading, under the general term of load losses, as Mr. Lewis has suggested.

I would make a similar suggestion with respect to rotating machines also, where the same difficulties have appeared in the rational classification of losses. The resistance loss in the armature winding does not seem to be logically excluded from the term load loss. Moreover, the losses due to magnetic leakage, which are properly included under the general term of load losses, may not properly be designated as stray losses, since they are included with the armature resistance loss, windage and friction, in the short-circuit core loss. The results of tests given in the papers by Messrs. Foster and Knowlton, and by Mr. Brainard, seem to indicate that these losses, as measured by this method, are not "greatly exaggerated," as stated in section 115 of the present rules, but that they are approximately the correct losses for the normal load condition.

Returning now to losses in transformers, an independent discussion of the various elements of loss and their classification may be useful. I will begin this by summarizing these elements, thus: The total losses of the transformer may be divided into those due to excitation, called no-load losses by Mr. Lewis, and those due to load, which he calls load losses. The former, ordinarily referred to as open-circuit or core loss, includes, besides hysteresis and eddy current losses in the core, a small element of resistance loss in the primary winding due to magnetizing current and a dielectric loss in the insulation which is very small in low-voltage transformers, but may be quite large in very high voltage transformers. These losses should be measured with open secondary, at rated frequency and rated sine wave voltage plus IR (instead of rated voltage minus IR). This correction of sign will be approved at once when it is considered that the rating of the transformer is based upon its output, and that the current rating is universally calculated from the name-plate voltage. The nameplate secondary voltage must, therefore, be taken as the full-load voltage, while the primary applied voltage is supposed to be in excess of the name-plate primary voltage by an amount equal to the transformer drop. The excitation of the

core corresponding to full load at 100 per cent power factor, is, therefore, the name-plate voltage plus the percentage of I^2R drop in the secondary winding.

The load losses include the losses due to magnetic leakage plus the I^2R loss due to load current and the measured resistance plus the extra loss due to the combination of load current and exciting current in the primary winding. This does not include the loss due to exciting current alone, which was measured with the open-circuit loss. The losses due to magnetic leakage and the I^2R loss due to load current are included in the measured short-circuit or impedance loss, but not the extra or stray loss due to exciting current. This loss is usually very small, but may be included by a correction, based not on the total short-circuit loss, as stated in equation (**24**) by Messrs. Fortescue and McConahey, but on the I^2R loss due to load current. Moreover, the total exciting current does not enter into this correction, but only the fundamental component of the exciting current. The correction may then be made exact, including the effect of the hysteresis angle, by the formula:

Total loss in copper − loss due to magnetizing current alone = extra loss due to magnetic leakage + resistance loss due to load current $\times [1 + 2\,pq\,(\cos\theta\,\cos\theta' + \sin\theta\,\sin\theta')]$* where

$$p = \frac{n_1\,(I_e)_1}{n_2\,I_2}$$

and

$$q = \frac{\left(\frac{n_2}{n_1}\,I_2\right)^2 R_1}{\text{total resistance loss due to load current}}$$

*The derivation of the formula given above for correcting I^2R loss to include stray loss due to exciting current is obtained as follows:

Referring to Fig. 2, page 602, the fundamental component of exciting current,

$$/I_e/_1$$

may be separated in two components a and b, the former in phase with the load current, the latter at right angles to it. Represent the load current in the primary winding

$$\frac{n_2}{n_1} I_2 \text{ by } c.$$

The total loss due to these currents is

$$[a^2 + (b + c)^2]\,R_1 =$$
$$(a^2 + b^2 + c^2 + 2bc)\;R_1$$

The loss due to the fundamental component of exciting current alone is $(a^2 + b^2)\,R_1$. The loss due to the harmonics of exciting current must be added to this, but these components do not affect the extra loss due

and where

$$\cos\theta = \text{power factor of the load}$$

and

$$\cos\theta' = \text{power factor of } (I_e)_1$$

$$(I_e)_1 = \text{fundamental component of exciting current}$$

With 10 per cent exciting current, which is the maximum value that should occur in practise, the fundamental component would probably be about 8 per cent, so that $p = 0.08$. Assuming a core loss of one per cent, we have $\cos\theta' = 0.125$, and sine $\theta' = 0.993$. Assuming equal resistance losses due to load current in the primary and secondary windings, we have $q = 0.5$. Now, for full load at 100 per cent power factor, the correction for stray loss due to magnetizing current becomes

$$I^2R \times 2 \times 0.08 \times 0.5 \times 0.125 = 0.01\, I^2R$$

and for full load at 80 per cent power factor,

$$I^2R \times 2 \times 0.08 \times 0.5\,(0.8 \times 0.125 + 0.6 \times 0.993) = 0.056\, I^2R$$

Thus the maximum correction that would be made for 100 per cent power factor load is about one per cent of the resistance loss due to load current, and this becomes about 5½ per cent for 80 per cent power factor load. It appears that this correction is hardly worthy of consideration in questions of efficiency. This is particularly true if we remember that the rise in temperature of the windings while the losses are being measured may produce an increase in the loss as great as or greater than the correction which we are considering.

---

to the combined exciting and load currents. The total I^2R loss in primary, minus the loss due to the exciting current alone, is

$$(c^2 + 2bc)\, R_1$$

Now

$$b = /I_e/_1 \cos(\theta' - \theta)$$

$$= p\,\frac{n_2}{n_1}\, I_2 \cos(\theta' - \theta)$$

$$= p\, c \cos(\theta' - \theta)$$

whence we have: Total I^2R loss in primary loss due to exciting current alone

$$= c^2\,[1 + 2\,p \cos(\theta' - \theta)]\, R_1.$$

Adding the loss due to load current in the secondary, and remembering that $c^2 R_1 = q \times$ total loss due to load current, we have:

Total loss due to load current, plus stray loss due to exciting current = total loss due to load current $\times [1 + 2pq\,(\cos\theta \cos\theta' + \sin\theta \sin\theta')]$

This increase in the copper loss due to temperature rise in the windings while the loss measurements are being made, seems to deserve more detailed consideration. Full-load current must be sent through the windings for this measurement, and at the start, all of the heat produced is stored up in the copper itself. As the temperature of the copper rises, it throws more and more heat out through the insulation into the oil, until the heat thrown out is equal to the heat generated, when the temperature ceases to rise, except as the temperature of the oil rises. The initial rate of temperature rise is therefore fixed by the thermal capacity of the copper and the rate at which heat is generated. The thermal capacity of copper is about 177 joules per pound and the average loss in large transformers is about 10 watts per pound. This gives an initial rate of temperature rise of one deg. in 17.7 seconds, or 3.4 deg. per minute, and an increase in the copper loss of $3.4 \times 0.4 = 1.36$ per cent.

This effect of temperature rise in compensating for the stray loss is illustrated by reference to Table I, showing the results of tests, at the end of the paper by Messrs. Fortescue and McConahey. We see here that the measured loss is larger at high power factors than at low, whereas the correction for stray loss would indicate that it should be smaller. (The stray loss was, in this case, included in the measurement by the method of the test.) This is explained by the fact that the high power factor readings were taken last, and that the loss was increased due to increase of temperature during the tests more than it was decreased by increasing the power factor. These results would have looked very different if the measurements had been taken in the reverse order.

The temperature tests recorded by Mr. Lewis under the heading "Relation between Impedance Watts and Load Losses," in Tables VII and VIII, are, of course, not comparative tests between impedance watts and load losses, but between loads of different power factors, since the exciting current is present in both cases, the only difference between the two cases being that of phase relation between the exciting current and the load current.

Although, as we have seen, the stray loss due to magnetizing current is not ordinarily important from the standpoint of efficiency, still it may be sufficient to account for a considerable difference in temperature rise between two transformers tested together by the opposition method, when this test is made with loading voltage and exciting voltage of the same frequency. The power factor of the load, or circulating current, depending as it does upon the relative amounts of inductance and resistance in the combined impedance of the transformers, is always low, giving almost the maximum correction for stray loss. The correction for one transformer will be positive and that for the other negative, since, while the current lags in one, it leads in the other, the difference in phase of the circulating current in the two trans-

formers with respect to the exciting current being 180 deg. The difference between the copper losses in the two transformers is thus twice the correction for one. There is, of course, a slight compensation for this difference in copper losses, due to the fact that the core loss is somewhat increased in the transformer having the smaller copper loss, and vice versa. The net result, however, may be a difference of two or three degrees in the temperature rises of the two transformers.

Equality of losses may be obtained by using a frequency for loading which is different from that used for exciting. This difference in frequency may be very slight, if desired, maintaining practically the rated frequency both for the excitation and for the load. This is, of course, a necessity for normal core loss, and it is also a necessity for normal copper loss when the eddy current losses are appreciable. The extra loss due to the combination of exciting current and load current will not be present under these circumstances, but only the sum of their respective independent losses.

The mathematical discussion given by Messrs. Fortescue and McConahey, under the second heading, "Theoretical Study of Copper Losses in Transformers," is correctly applicable to mutual inductive circuits in air (with no iron core). However, the values of equivalent resistance and equivalent inductance, given in equations (**7**) to (**13**) inclusive, are not completely expressed. The expressions given are the equivalent values for the nth harmonic only. The equivalent values which must be taken in connection with the value of the total resultant current depend upon the wave form of the current, *i.e.*, upon the relative values of the various harmonics of current. These values of resistance and inductance cannot, therefore, be expressed independently of the current. The complete expression for equations (**7**) and (**8**) would be

$$R_a = R_1 + \frac{\sum\left(\frac{n^2p^2M^2}{(R_2+R_0)^2+n^2p^2(L_2+L_0)^2}(I_1)_n^2\right)}{I_1^2}(R_2+R_0)$$

and

$$L_a = L_1 - \frac{\sum\left(\frac{n^2p^2m^2}{(R_2+R_0)^2+n^2p^2(L_2+L_0)^2}(I_1)_n^2\right)}{I_1^2}(L_2+L_0)$$

The remaining part of the discussion, if completely expressed, as it must be for any practical application, will be more complicated than it appears in the paper.

I do not agree with the authors that the results obtained in this manner, based upon the assumption that L_1 and L_2 and M are constants, apply with almost equal accuracy to transformers,

where these values vary, not only for different values of maximum inductance, but throughout the cycle for any given value of maximum inductance. This introduces additional harmonics in both current and voltage not taken into account in this treatment, the object of which is to cover the effects of harmonics.

The authors have made no practical application of this mathematical discussion. They state that formulas given in Section 5 of the paper are based upon it, but these formulas take no account of harmonics, and are very easily derived from considera-

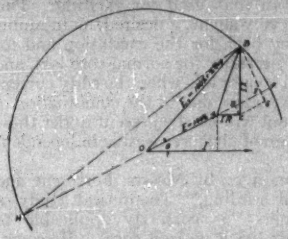


FIG. 1

FIG. 2

tions based upon a simple sine wave. Thus, referring to Fig. 1, the formula for regulation is derived as follows:

E_0 is the no-load voltage of the transformer and E the full-load voltage at the secondary terminals, so that

$$\text{regulation} = \frac{E_0 - E}{E} = \frac{AD + DF + FG}{E}$$

$$= \frac{IR\cos\theta + IX\sin\theta + FG}{E}$$

$$\text{But } FG = \frac{(FB)^2}{FH} = \frac{(IX\cos\theta - IR\sin\theta)^2}{2E + 2IR\cos\theta + 2IX\sin\theta + FG}$$

whence

$$\text{regulation} = \frac{IR\cos\theta}{E} + \frac{IX\sin\theta}{E} + \frac{\left(\frac{IX\cos\theta}{E} - \frac{IR\sin\theta}{E}\right)^2}{2 + \frac{2IR\cos\theta}{E} + \frac{2IX\sin\theta}{E} + \frac{FG}{E}}$$

and, multiplying by 100,

$$\text{per cent regulation} = \%\, IR \cos\theta + \%\, IX \sin\theta + \frac{(\%\, IX \cos\theta - \%\, IR \sin\theta)^2}{200 + 2\%\, IR \cos\theta + 2\%\, IX \sin\theta + \dfrac{FG}{E}}$$

Neglecting the last three terms in the denominator of the third term, we have the formula given in the paper, which, though sufficiently accurate for practical purposes, is thus seen to be inexact, apart from any consideration of harmonics.

Mr. Lewis has done the Institute an important service by including in his paper a large amount of data on the extra losses in low-voltage transformers, due to the magnetic leakage field, and in high-voltage transformers, due to the dielectric field. It is possible that the values given for extra loss due to magnetic leakage (called stray loss by Mr. Lewis) are, in general, too large, being the total measured loss minus the loss calculated from the measured value of resistance and the current. The increase in temperature during the measurement of this loss gives ordinarily too high a value, as explained above. Moreover, many of the worst cases are seen to be those of magnetic shunt transformers, in which the losses in the shunts themselves are included.

While these losses may be kept to a minimum value by careful design, and are practically eliminated in many cases, yet Messrs. Fortescue and McConahey must agree that commercial requirements as to rating and service, and conditions of design, are often such as to make it practically impossible to avoid quite large losses due to eddy currents.

These cases may be recognized, however, and the calculation of these extra losses usually can be made with sufficient accuracy for a basis of efficiency guarantee. In my opinion, therefore, the common practise of excluding these losses from efficiency guarantees is not necessary, nor desirable.

C. Fortescue: When the paper referred to by Mr. Weed was written, the authors had in mind both the eddy current losses in the copper, which are easily measured, and the portion of the I^2R loss due to the exciting current which is not included in any of the usual measurements. A portion of the I^2R loss due to the exciting current is included in the core loss measurements, and properly so, since it is practically constant at all loads. It is necessary to apply a correction to the short-circuit measurement for the other portion of the I^2R loss, but only when the exciting currents are very high, since otherwise this correction is negligible.

Mr. Lewis in his paper tabulates the stray losses and impedance voltages in a number of commercial transformers, and points out that there is apparently no definite relation between these two quantities. I have stated in my paper that in a good design the eddy loss in the conductor can be reduced to a very small value. It might be well to modify this statement by

adding that when high impedance is required, the cost of keeping down eddy currents to a low value sometimes becomes excessive. In transformers for furnaces, in which very large secondary currents are required, it becomes particularly difficult to keep this stray loss down. In the ordinary run of transformers, however, this loss can be controlled without materially adding to the cost.

James Burke: I simply desire to call attention to one feature of the paper by Mr. Lewis, which recommends the measurement of the copper losses hot, whereas the universal practise, I think, in this country now on transformers is to take the copper loss at 25 deg., and I simply wish to call attention to the fact that the recommendation of Mr. Lewis is a departure from the existing commercial practise, which is in use in connection with a very large number of transformer manufacturers.

I would like to bring to the attention of the Standards Committee another feature which might be considered in the new rules, and that is, sometimes manufacturers are asked to guarantee the volt-ampere efficiency of transformers, and I have seen specifications asking for the volt-ampere efficiency at 100 per cent power factor, 90 per cent power factor, and 80 per cent power factor, and I think it would be of advantage if the Standards Committee introduced some simple methods of bringing these factors into consideration rather than calling for specific tests under each of these conditions for acceptance tests.

E. A. Wagner: I think Mr. Burke's point about the volt-ampere efficiency is well taken. There has been a very pronounced demand, especially in the railway signal service, for figures giving volt-ampere efficiency. There is nothing really specific in the present standardization rules showing how this shall be done, and I think that the Standards Committee should mention this matter, and state absolutely clear definitions of the meaning of volt-ampere efficiency and also decide as to the effect of the excitation current on these volt-ampere efficiencies.

In regard to these recommendations at the end of Mr. Lewis's paper, I do not think that the exciting current should be deducted and segregated from the core loss measurement, that is, the effect of the exciting current on the copper losses. In a transformer designed for high exciting current, necessarily the core losses have been affected, due to that design, and as the exciting current is really a function of the core loss design, I think it should be included in the heading "no-load losses," or else a separate definition made as to the no-load losses which will include the effects of exciting current. Where the no-load losses are to be taken on the primary circuit, according to these recommendations, then it is going to make considerable difficulty in measuring losses on high-voltage transformers. We do not measure the core losses on 100,000-volt transformers on the primary side, we always measure them on the secondary side. The same holds true in the case of commercial transformers, 2200

volts to 110. We measure them directly with a 110-volt wattmeter, and do not attempt to step-up and then step-down.

The last recommendation reads: "On account of the variation with temperature, all losses should be measured at the operating temperature." If the Standards Committee adopts this recommendation, it should be specific as to a definite temperature. As a matter of fact, core losses go down with the increase in temperature, so that it affects the total loss in that way; but it is difficult to hold the temperature steady at any predetermined point if any time is consumed in making the measurements of these losses, and I think, therefore, it is better to specify a room temperature, and take the iron loss or no-load loss at that temperature, and if the full-load losses, including copper losses, are wanted, they can be corrected for the rise in temperature.

Charles P. Steinmetz: When the first Standardization Rules were established in 1899, it was stipulated that all losses should be measured at the full-load operating temperature. Transformer losses were included in this rule.

Before that time they had been measured by the manufacturers at the room temperature and the efficiency guaranteed on that basis, and these guarantees were wrong. That question has frequently arisen, and transformer designers have come before the Standards Committee and requested that the Rules should be changed to read: "In all apparatus the losses shall be measured at the full-load operating temperature, except in the case of transformers, where they shall be measured at the room temperature." It is not desirable to make a specification of this kind for transformers. There is no reason whatever to be seen why this should be done. The efficiency you want to know is that at which the transformer is running, which is at the operating temperature, and not at some fictitious temperature. It is true that it means that you must lower the efficiency guarantees a little, but that cannot be helped. What you guarantee when measuring the I^2R losses at the room temperature, is not the efficiency of the apparatus, but a higher value than is actually there.

The I^2R loss of the exciting current should be separated and not included in the core losses. The I^2R loss of the exciting current changes with the load. For instance, if the exciting current is 10 per cent of full-load current, then at no-load the I^2R loss of the exciting current is 1 per cent of the primary I^2R loss, and conversely the primary I^2R loss at full non-inductive load is 100 times the I^2R loss at no-load. But at full inductive load the exciting current increases the load current by 10 per cent, and so gives an additional primary I^2R loss of 21 per cent, and that means at full inductive load the primary I^2R loss is 121 times as high as at no-load. Obviously, therefore, the I^2R loss due to the exciting current must be considered separately and not included in the no-load losses.

Leo Schuler: I call your attention to the fact that when you measure the efficiency of the transformer at room temperature, instead of working temperature, it does not mean necessarily a very great difference in the efficiency, because the copper losses, of course, are lower, but the iron losses are higher, especially with alloyed iron.

James Burke: I want to correct any misunderstanding of what I said. I am not advocating measuring the transformer losses at room temperature. I was simply calling attention to the difference between the commercial practises of today and the recommendations.

Charles F. Scott: In regard to the word "stray," if I am not mistaken, laboratory manuals present the "stray power" method of measuring efficiency which is taught to the student as a very definite thing. Stray power is about everything that I^2R does not include. The power to drive a motor is measured at no-load, and what is not I^2R is stray power.

I asked this morning one of the designing engineers of one of the large companies, whether the term "stray power" was used in his organization. He said he did not know that it was. We come here and find the word "stray" used indiscriminately to cover about everything which cannot be accounted for.

The moral of this is that one of the chief duties of our Standards Committee is in the matter of definitions. Here is a term "stray," that certainly needs to be defined.

J. M. Weed: I think Mr. Wagner's objection to measuring the core loss from the primary side is based upon an erroneous definition of the primary side. The primary side is often the low-voltage side, as the transformer may be used either for raising or for lowering the voltage.

J. E. Saunders: I notice the recommendation is that transformer losses are to be measured at operating temperature. I want to know what this operating temperature is. We are hanging transformers where it is 130 deg. fahr. in the shade in the summer time, and they are hanging out all summer, and we are hanging them in another place where it goes as low as 30 to 40 deg. fahr. below zero, in the winter time, and those are the operating temperatures, so I want to know why we should not substitute room temperature for operating temperature.

C. Fortescue: The operating temperature, I think, is defined as the temperature at which the transformer will operate at the standard room temperature of 25 deg. with full load, at 100 per cent power factor. In transformers we base our rise on the average temperature of the coils as measured by the rise of resistance method. We do not indicate the temperature of the hot spot. In transformers there is a very slight difference between the average temperature of the coil and the maximum temperature, on account of the small temperature gradients through the insulation, and coils, etc.

J. M. Weed: There is one point which I think should be recognized by the Standards Committee in laying out their

rules, and it may be that some of the members present might wish to discuss the matter if it is brought out specifically, and that is the question of cooling after the load is taken off the transformer. This, of course, applies to all electrical apparatus. It is practically impossible to get the resistance measurements at once, of course, and it is a fact that the apparatus is cooling after the load is taken off until such time as the resistance can be taken. It is possible, as has been brought out in some of these papers, to make corrections, but this matter of correction is always an uncertain matter, and will involve complications, and it would possibly be better to specify a time limit within which the resistance measurement should be made, recognizing the fact that the actual temperature at the instant that the load is taken off is a little higher, but considering it on the same basis as the hot spot that we cannot find.

A Member: There exists a method for finding the real temperature which is much easier than to find the hot spot. You have only to know exactly the moment when you really take the load off the transformer. Say that you press a stop watch at this moment, and then take two or three readings afterward, plotting a time-heat curve, and extrapolate that curve, you get the correct value the moment that you really took the load off the transformer.

L. T. Robinson: In connection with the remarks of the last speaker, I would say if those who are interested will refer to the paper which was read here yesterday by Mr. Chubb, they will see that the extrapolated value will not always be correct. Under some conditions the part where you are taking the temperature by resistance goes down after a while, and then it begins to go up by transfer of heat from some iron part or something else that is hotter. It may be useful to use extrapolation sometimes, but it must be used with caution, otherwise you may get a large error.

J. M. Weed: In determining the temperature by extrapolation the results are very uncertain, for the reason that slight inaccuracies in the readings modify the shape of the curve very much. The point that you decide upon as the initial temperature is very much influenced by errors in the first two or three points of the curve.

C. Fortescue: I agree with Mr. Weed that the method of extrapolation by means of a curve is very uncertain and brings in a large personal factor. It may be necessary in some cases to use such methods, but it would be better if some quicker methods could be devised for measuring the resistance of the windings than those at present in use. One thing that can be done in using the Kelvin bridge or the Wheatstone bridge is to have them set for the expected reading; in this way the final adjustment can be made very quickly. A measurement made in this manner is so quick that I believe only one or two degrees are lost. A matter of one or two degrees has but little effect on the operation

of a transformer, and therefore I think measurements obtained in this way are sufficiently accurate.

Paul M. Lincoln: A definite question has been asked as to what temperature shall be used in calculating the copper losses of transformers and other apparatus, and I think this question is one which requires a definite answer and one which should be fixed by the Standardization Rules when promulgated. It seems to me that it is best answered by adopting the suggestion made in Mr. Lewis's paper, namely, to base it upon the operating temperature. But that operating temperature should be taken above a standard air temperature, and in my opinion that standard air temperature should be taken at 25 deg. cent. Therefore, the copper loss in a transformer should be calculated at the temperature at which it will actually operate when the surrounding air is 25 deg. cent.

W. C. Smith: In connection with the question of losses just brought up, and also referring to the statement of Dr. Steinmetz this morning, in which he said that the customer is most interested in losses at the operating temperature, there is another question regarding efficiencies which should be touched upon by the Institute, and that is the question of efficiencies at fractional loads. The present rules imply that the efficiency at a given load should be based on the operating temperature at that load. In the case of fractional loads, this imposes a serious burden on the manufacturer, one that is not complied with nowadays or asked for. Fractional-load efficiencies are guaranteed at the same temperature as the full-load efficiencies, so I believe that the new Institute Rules should state clearly that all efficiencies, both for full load and fractional loads, should be based on the full-load operating temperature.

J. M. Weed: I would suggest that it ought to be satisfactory to specify the efficiencies of the transformers at temperatures at which they are guaranteed to operate at full load; that is, with standard room temperature, if you guarantee a transformer for 35 deg. cent. rise, with a room temperature of 25 deg. cent., base the efficiencies of that transformer on the losses at 60 deg., and if you guarantee 50 deg. cent. rise over 25 deg. cent. room temperature, you guarantee your efficiencies on the basis of 75 deg.

W. C. Smith: Inasmuch as I brought up this point, I would like to go on record that I concur fully with the two gentlemen who have just preceded me—in my opinion, all efficiencies should be based on the full-load guaranteed operating temperature.

G. K. Kaiser: Referring to the question of operating temperatures, it appears to me that the regulation as well as the efficiency should be based on the temperature which the apparatus assumes when operating continuously under load. That is, the regulation at various loads and power factors should be determined from the *load losses* at operating temperature and the reactance of the transformer.

(e) Brush Losses

W. B. Brady: Referring to the paper by Messrs. Edgecomb and Dick, the brush manufacturers are very much interested in the subject of brush losses and we are very glad the Institute has taken up this matter. We have been working on the development of brush tests for more than six years but we have been handicapped by the lack of apparatus that would give us consistent results. Then, again, as we have developed our own apparatus the results we got were applicable only to that apparatus and only under the exact conditions of that test. This is due to the number of variables and losses that are in a certain combination under the conditions of that test. By having these losses more definitely separated and understood we may be able to get a definite basis to make our results comparable. One of the best ways I know of is to standardize the brush-testing apparatus and I hope this can be done in the very near future. It will be a decided step in brush development which will be of great assistance to engineers.

Leo Schuler: I ask whether any experiments have been made in this country with regard to the influence of the current flowing from the commutator to the brush, in relation to the friction. It is rather surprising, but it is a fact, that friction is somewhat influenced by the current on the brush. I cannot see the reason for it, but there may be a molecular attraction on the surface of the commutator.

B. A. Behrend: In regard to Mr. Schuler's question, whether the coefficient of friction depends on the current in the brush. If an experiment is conducted on an electric motor or generator, very many vitiating factors enter into it, so that it would be impossible to say that the presence of an electric current is responsible for the alteration or change of the coefficient of friction, and I ask Mr. Schuler whether he means that under stationary conditions such change or variation in the coefficient of friction is obtained?

Leo Schuler: I do not know whether in those cases it would affect it or not. What I know is this: With a slip-ring arrangement, driven by a small synchronous motor, just sufficient to drive the slip-ring with the brush on it, that synchronous motor falls out of step the moment you put current on the brush. That seems to indicate an increase of friction due to the current.

There is another reason. When you work a machine idle, that means excited, but no current on, then you hear a certain noise produced by the friction of the brushes on the commutator, and you will notice quite a pronounced alteration of this noise, when you put current on; there seems to be no other explanation for this than that there is another coefficient of friction when the current is on the machine.

B. A. Behrend: May I ask whether it is not possible that this additional power required in your synchronous motor is due to current induced in your slip-rings and in your brush? You would expect such induced currents, would you not?

Leo Schuler: But I cannot see how power is taken from the motor for these eddy currents.

B. A. Behrend: That seems to be the critical point at issue; if there is any possibility of this applied power having to come from the synchronous motor, it would not be charged to coefficient of friction.

Leo Schuler: I think if there are induced currents in the slip-rings then the power to produce these currents can only be taken from the source of current which is going through the slip-rings, but not from the motor driving the slip-ring.

B. A. Behrend: I would not be so ready to endorse that statement; it does not seem to me to be absolutely evident that it is so. Perhaps some one else has thought more about that point, and can give us some information regarding it. I ask Mr. Lamme whether it is not possible that the creation of a magnetic field by an electric current and its consequent passing through the slip ring would not account to some extent for the falling out of step of the synchronous motor driving the device. I do not know that this is the explanation in the specific case cited, but it seems perfectly plausible to assume the existence of such a magnetic field through which the slip-ring has to cut at a certain definite rate of speed which would put an additional load on the driving synchronous motor. I may be mistaken in my explanation, but it is entirely reasonable.

W. B. Brady: Answering the question about the influence of current on the coefficient of friction, Messrs. Martindale and Berkeley in their written discussion indicate that the coefficient of friction decreases very materially with increase of current. We tried that under four different grades of carbon on the slip-ring, simply a band of copper mounted on a pulley, and measured the friction in that way. It decreased very materially with increased current.

A. H. Freeman: We have made no particular tests to determine the effect of current density on coefficient of friction, but my observation has been, on some temperature results, it may have that effect Mr. Brady speaks of, that the coefficient of friction drops slightly with increased current densities. In the paper by Messrs. Edgecomb and Dick, I see that they recommend a set of constants for representing the difference between the surface of the test apparatus and the surface of cast-iron, steel, bronze and various other materials.

Alexander Gray: About a year ago I started some students on experimental work on brush friction and the results they obtained were so erratic that no satisfactory conclusion could be drawn from them. Recently I started up the same apparatus and found that the coefficient of friction could vary 300 per cent in half an hour. The friction force was measured by a spring balance at the end of a beam which was supported on ball bearings concentric with the shaft of the motor and which carried two brushes at opposite ends of a diameter. At the

start, the pull on the scale was about one pound; at the end of half an hour the pull had gone up to two pounds, and the temperature of the brush, measured by a thermocouple placed within 1/16 in. of the rubbing surface, also increased. The brushes then began to chatter, the temperature rose very rapidly to several times the previous value and the pull on the scale went up to 3.5 pounds. One of my assistants came into the laboratory at that time; he was smoking and blew a cloud of smoke on the ring; the scale reading went down immediately to 2 pounds, the chattering stopped and the temperature dropped considerably; the chattering did not commence again nor did the pull on the scale reach the value of 3.5 pounds for about one minute. Afterwards, as a matter of curiosity, I ran my finger across the ring surface, the pull immediately dropped to two pounds, the chattering ceased, and both took about one minute to rise again to the original value. A piece of waste was then put in contact with the running ring and was left there for half an hour, at the end of which time chattering had ceased and the scale reading had come down to one pound, and then, although the waste was removed, the pull did not increase in two days, for which length of time the apparatus was kept running continuously. A bunsen flame was then applied to the ring, and although the friction pull decreased, the decrease was very small. A little vaseline was then put on the ring and the scale pull came down to a smaller value and stayed there.

After a thin film had been ground from the brush contact it was possible to reproduce the same cycle of operations.

In case there should be any misunderstanding, I may say that the brush was a modern one, and had a highly polished surface. The film on the ring was not something I put on myself, but was inherent in the brush.

The above results seem to me to be of such importance that I would be tardy in standardizing certain coefficients of friction for certain standard machines, in fact I consider the proposition to be very objectionable. Brush friction depends largely on the design of the holder and on the workmanship put into the brush mechanism. If I buy a machine with a certain guaranteed efficiency I want to measure the efficiency or losses in some way or another, and shall not be satisfied with something calculated by the manufacturer from constants, even although they are standardized by the Institute.

If the brush friction is measured when the brushes are newly ground a certain result is obtained; if the machine is then run for several hours the friction loss may increase 300 per cent, but by running a piece of waste across the commutator surface for some time the friction loss can be reduced again. This being the case, I would suggest that the new rules make some recommendation as to when the friction loss shall be measured, whether before or after the heat run, and also as to whether or not the manufacturer should be allowed to clean the commutator before he measures this loss.

Comfort A. Adams: I think we will all agree that the whole question of satisfactory operation of commutating machines, as to the commutator and brushes, is one which depends upon a very great many details not only of manufacture but also of care and operation. There are many variables involved, and it is difficult to lay down general rules. It is not anything you can theorize much about, one way or the other. I will simply state what I have found to be the most successful method of operating commutating machines from the purely practical standpoint. This applies to modern, good quality commutating machines, with brushes such as are ordinarily supplied. Start with the commutator in perfect condition, as far as it can be made so, and the brushes well fitted; then watch it very carefully for the first few days, or possibly a week. During the first day of its operation be very sure to keep the commutator so clean and in such condition that it will not cut. I assume, of course, that the machine does not spark enough to burn. After the polished condition has been once established, very little care will keep the commutator in good operating condition without any lubrication. In fact, my experience has been that there is more danger with lubrication than without, after the commutator is once thoroughly well polished and is in good working condition. It is not sufficient, in the case of a freshly ground commutator, to clean it off once and let it run for a day or two without any care at all. It is only after it has become thoroughly polished that it can be allowed to go with occasional care, and the principal thing is to keep it clean and dry. There is a little lubrication in these brushes, but much of it is apt to gum up the commutator and a little sparking will cause the coefficient of friction to rise very rapidly.

Alexander Gray: The work presented to us in these papers is excellent and we ought to be grateful to the writers for the amount of work they have put into them. I know what the measurement of the coefficient of friction on brushes means. The point we are concerned with, however, is not the angle of the brushes—we are not going to test for that; we are looking for a suitable performance test for brush friction loss and instructions as to how to make it.

As Professor Adams says, the proper thing to do is to take care of the commutator for two or three days and then let it run; but if you tell the manufacturer you want the machine to run for a week before you test it, he will probably increase the price. The point I want to make is that we might hurry this first part of the business by cleaning off the film which is deposited and so allow the brushes to take the bedding sooner than two or three days. If we can do that, let us standardize it; if we cannot do it, let it alone.

In regard to the suggestion that the smoke was a lubricant, it is ingenious and it may be right. The smoke may also act as an

abrasive which cleans off the film of carbon; the same man blew on the commutator when he was not smoking and it made no difference to the friction loss, so that we can eliminate the question of moisture.

B. G. Lamme: Mr. Schuler has raised a point about the effect of current on brush losses. I will say that under some conditions current may have a great effect on the total losses in connection with collector rings. In the case of very heavy rings carrying very heavy currents, the magnetic field set up by such currents, if cut by the collector rings, may be such as to cause very heavy eddy current losses in the rings themselves. In the case of a 2000-kw. unipolar generator with which I am familiar, in the preliminary tests, one-half of the rings on the machine were made of steel, instead of bronze, and on the test with normal full load current under zero voltage conditions, the measured loss was approximately 200 kw. higher than when all the rings were bronze. Our investigation showed that the excess loss was due almost entirely to eddy currents due to magnetic action, and was not due to brush contact. The loss was almost entirely in the rings themselves. With bronze rings there was some loss, but not more than a few per cent of that found with the steel rings. In this case, therefore, the losses varied with the current, and such losses were carried by the driving motor.

Apparently there are two opposite opinions regarding this variation of friction with the current, one claim being that it is reduced with the current and another that it is increased. It seems to me that an action other than the eddy currents above described may also be present, namely the influence of the direction of current on the brush contact itself. Our test with the unipolar generator referred to, showed that where the currents passed from the brushes to the rings, the rings tended to take a good glaze, and but relatively little attention was required in the way of cleaning; whereas, where the current passed from the rings to the brushes there was a continued tendency to burn away the surface of the rings and to increase the resistance of contact. Apparently, one of these actions should give less friction loss than the other, and possibly in the conflicting opinions cited, the different results may have been due to different arrangements of testing which did not take the direction of current into account.

In the question of brush friction losses, especially on new machines, the condition of the commutator itself must be taken into account. Until commutators are well "seasoned," they are liable to show high brush friction losses. The binding material in the commutator mica may ooze out to a very slight extent, and "gum" the commutator slightly. This will increase the friction enormously, but as it is obviously impossible to thoroughly season every commutator before shop test, it is necessary to put the commutator in the best possible shape for such test, with the understanding that in practise, after it is well

seasoned, the losses will doubtless decrease materially. That is one of the handicaps on the manufacturer.

Alexander Gray: Should that seasoning be done by the manufacturer or should that seasoning be done by the purchaser? If we adopt certain standard friction coefficiencies, then it will have to be done by the purchaser. If we do not adopt these standards, the manufacturer will be at liberty to get his commutator into any kind of shape he likes, and we will test it when in that shape, and then the manufacturer will have to do the tinkering to the machine. Most of us would be quite satisfied, on an order of twenty machines, to get a test on one; to test all of the twenty would be somewhat of a nuisance. We do not expect elaborate tests on small machines.

R. B. Treat: The efficiency of direct-current machines will in the majority of cases be found to meet the specifications at the time of factory tests. Whatever reduction of brush friction occurs on the commutator after erection accrues to the advantage of the customer.

Commutator seasoning time may vary all the way from zero to six weeks or more, but the manufacturer's brush friction figures are usually based on results he can obtain in factory test.

One disturbing feature of brush tests on collector rings is the chattering. This often results from a slip ring loosening when it becomes warmed up. Some recent tests were conducted with taper shaft and ring fitted with a follow-up spring.

Many cases of very rapid brush wear were cured by the substitution of rings that could not become loose, even where the original ring could not be declared "loose" by hand examination.

Brush friction probably decreases as the current increases. The general result of many tests indicates this conclusion.

W. F. Dawson: I would suggest in explanation of Professor Gray's trouble with brush chattering that the trailing angle was incorrect and that a reduction in such angle would have stopped the chattering. The increased friction coefficient observed was probably due to the brush surface picking copper.

Alexander Gray: I am personally doubtful about a leading brush not chattering so much. My experience has been largely with machines having trailing brushes, and if these are rotated in the opposite direction the brushes will generally chatter.

B. A. Behrend: As Mr. Lamme has stated, there are so many mysterious factors about the commutator and the brushes and in the operation of commutators, that he has no hesitation in frankly saying so. Professor Gray, who has had wide experience in the operation and design of direct-current machines, has come to the same conclusion.

I do not think it is possible to adopt a specific brush angle. We have to run at all commutator speeds up to 8000 ft. These angles have to be adjusted, and it is often necessary to undercut the mica on some commutators; in other words, every possible

and suitable means must be resorted to in order to make the commutator run true and to eliminate the chattering of brushes. Chattering of brushes is due to some sort of harmonic disturbance, and it becomes cumulative at certain speeds and under certain conditions. The disturbing periodic force can occasionally be eliminated, and though the natural period of vibration remains, the external cause of chattering having been eliminated, the chattering has been stopped.

Under these conditions it seems to me it would be folly, as we are interested here in the subject of standardization, to lay down rules as to the coefficient of friction, as to the angle of the brushes, and as to a great many of these things which the manufacturer himself does not know anything about as yet. I was once talking to the chief draftsman of one of our large manufacturing companies, and I asked him if he had any standards. He said, "Why, Mr. Behrend, we have thousands of them." We are going to have thousands of standards if we have to lay down such rules at the present time, because we do not know enough about these things. Every day the field changes. The commutator of to-day is a very different piece of apparatus from what it was ten years ago.

F. D. Newbury: I believe Mr. Gray has been the only speaker who has kept to the point at issue in the discussion of the brush loss papers. The work before the Standards Committee, as Mr. Gray said, is determining how to measure brush losses and not how to operate machines.

In regard to brush friction, I do not believe that this measurement presents a very difficult problem, not so difficult as the determination of the other brush losses touched on by Mr. Wilson, losses of commutation, voltage drop, etc. Brush friction can be measured directly on the machine at the time the machine is on test at the manufacturer's plant. If such determinations do not fall within reasonable average values, it means one of two things; that the manufacturer must go to the expense of putting the commutator in first-class shape, which not only means seasoning so that there are no high bars or high mica, but running the machines a sufficiently long time to secure the dark brown glaze every one likes to see on a commutator; or that the customer accepts such average values, appreciating the fact that the commutator on shop test is not in the best condition. In the case of other brush losses, involving voltage drop, I believe we will be forced to an assumption of average drop per brush, or some such method as will be discussed tonight in determining additional losses.

L. E. Underwood: Regarding the running of brushes trailing, I am inclined to think that it is possible to run them trailing with success at slightly greater angles than 15 deg., possibly at 20 deg. or even 25 deg., although that depends a great deal upon the speed and condition of the commutator.

As for running the brushes leading, it is undoubtedly true

that for different speeds of commutator it is necessary, in order to get best results, to run a leading brush at different angles. That being the case, the practical application of leading brush holders on the same machine which is used for various and sundry speeds, seems to be quite a problem. I do not see exactly how the problem will be solved.

T. M. McNiece (by letter): The determination of brush losses is exceedingly difficult under any conditions. The actual values or results secured by tests are greatly influenced by the state of the surfaces of the sliding contacts. The duplication of these surface conditions on brushes and commutators is exceedingly difficult and it is a problem to determine whether or not these factors are sufficiently alike in successive tests to warrant definite conclusions.

In the paper by Messrs. Erben and Freeman, attention has been called to the effect on friction of various angles of inclination between the brushes and the commutator. In connection with this, a formula is given for calculating the watts lost through brush friction, and this formula is applied to a specific case.

Some question may be raised in regard to the accuracy of this formula. The effect of varying the angle of inclination of the brush with respect to the commutator may be well illustrated by the use of a force diagram. With holders of the box type, four forces may be said to be acting upon the brushes: (1) the pressure, P, applied to the brush in the direction of its axis; (2) the frictional force, W, at the brush contact, acting in the direction of rotation; (3) the normal pressure, N, between the brush and commutator; (4) the reaction H, of the brush holder. The line of application of this force is normal to the sides of brush and holder. The amount and direction of P and the direction of W are known and the amount of W determined by the test as made. The angle B is the angle between the brush and the normal to the commutator at the point of intersection between the axis of brush and the circumference of commutator.

If a force diagram be now constructed it will be seen that

$$N = \frac{P}{\cos B} + W \tan B$$

The formula in this form applies to those cases in which the brush is trailing. When the brush is leading the formula becomes

$$N = \frac{P}{\cos B} - W \tan B$$

The coefficient of friction may then be calculated from the formula $F = \frac{W}{N}$, where F is the coefficient of friction.

Substituting in this equation the values of N, for both trailing and leading brushes, we find that

$$W = \frac{F\,P}{\sin A - F \cos A}$$

for trailing brushes and

$$W = \frac{F\,P}{\sin A + F \cos A}$$

for leading brushes, where A is the angle between the brush and the tangent to the commutator at the point of intersection of the axis of the brush with the commutator.

When the brush is trailing, the normal pressure is found to be composed not only of the projection of the applied pressure, P, but also of the added projection of the reaction, H, of the brush holder. The forces, P and F, combine to make H of considerable moment in the trailing brush. The normal component of this latter force may be sufficiently great to hold a brush on the under side of the commutator without any spring tension and against its own weight.

The cause of the greater friction in the trailing brush may be said to lie in the greatly augmented normal pressure on account of this wedge action of the brush between the holder and the commutator. As indicated in the formula

$$W = \frac{F\,P}{\sin A - F \cos A}$$

for trailing brushes, there is a certain value of the angle A for each value of F, where theoretically W becomes equal to infinity. This is at the point where the tangent of the angle A is equal to F and the reaction, N, at this instant is infinitely great. Before this point is reached the holder or brush would yield, or the braking action would stop the rotation of the commutator.

In the leading brush, the action of the force W tends to decrease the wedge action of the brush as well as to decrease the applied pressure P. As a result of this, the normal pressure is greatly decreased, with a consequent reduction in friction. The formula in the paper under discussion would therefore take the form

$$W = \frac{P \times F \times V \times 746}{33000\,(\sin A + F \cos A)}$$

Sufficient work has not been done along these lines to enable us to say how closely results may be expected to agree with the theoretical formula, or what correction factors may have to

be applied in order to make this equation of working value. A later report will be made as soon as definite results are secured.

There is always a certain degree of eccentricity which may cause a very slight rise and fall of the brushes in the holders and it is possible that the slight friction between sides of the holder and the brush may affect the results to some extent. The clearance between brushes and holders may also exert some effect on these quantities.

Another factor which would undoubtedly have a considerable influence on this point is the rigidity of the holders, especially when the brushes are trailing. The brush holders on a friction testing machine should be rigidly constructed and supported, or they will have a great influence on chattering, which will seriously affect the frictional readings. A study of these conditions leads to the conclusion that trailing brushes demand much more rigid holders than leading brushes.

In view of the form taken by this formula, it is recommended that the characteristic friction tests made on any grade of brushes be made with the brushes in a radial position. The proper friction at any angle can then be calculated from this formula. This will simplify the tests very greatly.

L. R. Berkeley and E. H. Martindale (by letter): There is one phenomenon which has not been mentioned in this paper which is worthy of much investigation, namely the variation of friction with different current densities. The accompanying figures are an average of the results obtained on four different grades of carbon brushes, with comparatively high coefficient.

Amperes per sq. in.	Coefficient of friction
0	0.81
20	0.59
40	0.41
60	0.34
80	0.30
100	0.27

These results were obtained on a copper slip ring at a pressure of 2 lb. per sq. in. (70.4 grams per sq. cm.) and at a peripheral speed of 1000 ft. (305 m.) per minute, with brushes set in a radial position.

From the table it is seen that the coefficient of friction at 100 amperes per sq. in. (15.5 amperes per sq. cm.) is one-third as great as when no current is passing through the brush. The writers believe this may be due to a graphitization of carbon particles by the small electric arc which carries the current between the brush and the commutator.

This phenomenon cannot be explained by change in temperature, as artificial heat will not produce the same effect, in fact, heat usually tends to increase rather than decrease the friction.

After the current is shut off it requires from three to fifteen minutes for the friction to rise to the normal zero current value.

T. M. McNiece (by letter): As stated by Mr. C. E. Wilson, the contact drop losses are so intimately associated with others which may be termed commutation losses, that their accurate separation seems to be practically impossible at this time.

In practise the I^2R loss at the brush contacts is often so much greater than the loss which would be indicated by test on a slip ring or short-circuited commutator at the rated current density, that the tests may be said to give almost no indication of the loss to be expected at this point. It seems very proper to separate such losses from the brush losses if possible, and since they depend entirely on certain details of design and construction of the machines, the pure brush losses should be determined and increased by a certain factor which might be termed a commutating constant. This constant would be peculiar to the type of machine upon which the brushes are to be used.

It seems advisable in making contact drop tests, to make all standard tests upon radial brushes. In view of the great changes produced in the normal reaction between brush and commutator by running the brushes at various angles, and since this normal reaction also has great influence on contact drop, it would seem that these effects might be determined by the use of suitable constants.

The decreased friction secured by operating the brushes in a leading position cannot be said to be a net gain, as it may be assumed that under the decreased effective pressure, the contact losses will be increased to a certain extent.

The variations introduced by running the brushes at different angles are merely those which would be produced by changes in effective pressure and area.

From an analysis of the conditions accompanying the determination of brush losses, it seems that in friction losses as well as voltage losses, the most satisfactory methods for securing these results will be those in which the characteristic tests are applied under the most simple conditions and the results of these standard tests modified by the application of factors to be determined by the actual condition of operation. This system would result in simpler and more effective standardization of testing methods.

(*c*) Generators, A-C. and D-C.; and (*d*) Errors of Tests

John L. Harper: There are statements in the paper by Messrs. Foster and Knowlton which seem to warrant further consideration, reference being made especially to the first paragraph in the summary. The authors describe four methods of determining losses, in each of which it will be noted a different result was obtained.

These losses are measured for the purpose of determining the efficiency of the generators. Now, if the efficiency of a generator could be determined by the use of several different methods, which under the same conditions gave different results, this one generator at the same moment would have several different

efficiencies, depending upon the method used for determining the losses or upon the wording of the contract under which it was furnished, or whether the designing engineer had been so incorrect in his computation that it was necessary to boost the efficiency by a choice of methods.

It may be conceded that efficiency might vary with time or conditions, and that errors of measurement of energy and losses may exist. But it is undoubtedly true that a generator can have only one efficiency at one time.

I therefore believe that the Standardization Rules should be explicit and frank in the statement that the efficiency of an apparatus is a fact, and not a variable result depending upon the method of determination.

The gentleman who prepared the articles on efficiency in the old rules probably never intended that a manufacturer should claim the approval of these rules, in requiring a purchaser to accept and pay for apparatus as meeting efficiency requirements when such so-called efficiency determination was based on the shop measurement of certain segregated losses; when this same apparatus after being set up and tested by a method closely resembling the "circulating energy" method (mentioned in the paper as the most correct of the determinations), was shown to have additional losses which brought the efficiency down to about 3 per cent below the specifications.

As one of that part of the membership of the Institute which is not connected with the manufacturing interests, it is not my desire to put forward such methods of measurement of efficiency as will cause undue or unnecessary expense to the manufacturer, thereby increasing over-all expense which is added to prices which customers must pay; and it is far from my intent to assume that it would be right or proper to require small and stock apparatus to be sold under any special efficiency requirements.

It is only my desire to ask that, in the further consideration now being given the Standardization Rules, the word efficiency be considered to mean true efficiency; and that the Institute give its approval, for the purpose of determining efficiency, only to such methods as measure all the loss (within the limits of correctness of measuring instruments), and also such methods as represent a minimum probable error; and that any other commercial methods be accepted only as approximates of efficiency, and be approved only on that basis. What I want to bring out is that methods in which all the losses are not determined should not be used for efficiencies, but should be used in determining commercial approximations of efficiency which are approved on this basis. Therefore, in my opinion the drafters of the new rules should make clear what is intended by the term efficiency, and then so generalize the methods of determining the losses, that facts cannot be evaded, and still full leeway may be obtained for the adoption and use from time to time of more

correct methods of determining all the losses in electrical apparatus.

It is unfortunate that the classes of apparatus chosen by Messrs. Foster and Knowlton for these determinations are such that the difference in the losses determined by the segregated loss method and the "circulating energy" method appears to be slight, for in my own experience, gotten in the Niagara Falls district in connection with apparatus from the smallest to the largest sizes, it has come under my observation that in certain classes of machinery a difference of two or three per cent may be found in the losses as determined by the manufacturers according to the segregated loss method, and those found after erection, by methods which measure all the losses with minimum error and of the general form called "circulating energy" methods in the experiments of the above authors.

In general, in small apparatus the exact determination of efficiency is of little interest to the purchaser. In the larger, and often the special apparatus used in the Niagara vicinity, exact determination of efficiency is of vital importance, often representing the payment or non-payment of hundreds of thousands of dollars, and it is hoped that the Institute will not approve such methods of determining losses that the purchasers of this class of apparatus will be obliged to oppose the standards approved by the Institute, but may rather be assisted by them in obtaining correct efficiency determinations of any of their electrical apparatus.

Leo Schuler: In the German Standards Committee we have recently discussed very carefully the question of what we call "additional losses." We have tried to get some method for taking these losses into consideration, but so far we have failed. We have considered the proposition contained in your present rules, which takes one-third of the short-circuit loss, but this, I understand, is only intended for synchronous alternators. You do not give any hint how to check additional losses, in the case of direct-current machines or induction motors.

I have looked forward with great interest to what is to be said about this question here, but as far as I can see, it will be very difficult indeed for the Standards Committee to condense these papers into certain rules to be applied to all kinds of machinery, and I should strongly advise you, if you do not arrive at a very definite method of doing it, and I do not think you will, to leave the additional losses out altogether and do as we have decided to do, that is, call the efficiency measured by the separate loss method the "conventional efficiency" or something of that kind, an efficiency which is somewhat lower than the real efficiency, but you do not know how much lower it is. This proposition is not very good, but I think it will be the best you can do.

R. E. Hellmund: I wish to make a few remarks about the paper on "Losses in Commutating Machines," especially

referring to direct-current machines. The hope is expressed in this paper that it will be possible to get a constant percentage which should be added to the I^2R losses in order to take into account the stray losses. This, of course, would get the average efficiency slightly more correct, but it certainly would not show the merits of the various machines. The reason for this is that the stray losses are very numerous in direct-current machines, in fact in all commutator machines.

In the paper referred to, the authors mention only the commutation losses and the loss due to flux distortion. These are some of the most important losses, but there are a large number of others, which in some motors may be rather large. We have first the regular iron core losses, which, of course, are little influenced by the distortion, but even these may be somewhat influenced by the interpole flux which exists only at load. The same is true with regard to the core losses in the teeth. Here, as the paper mentions, the distortion of the main field is of importance, but the interpole flux may also add some losses at load. Further, there may be some extra losses in the surface of the interpoles, which are due to the fluctuations caused by the passing of the armature teeth. Then we have similar losses in the surface of the main poles, which also change with the distortion.

Further, if the relation of the teeth to the pole face has certain proportions, the total reluctance of the magnetic path changes, and this, of course, will tend to set up fluctuations in the main flux which in turn will set up eddy currents in the frame casting, as well as in the short-circuited coils under the brushes; this, of course, again means losses. It has also been shown that considerable losses may occur in the commutator bars, and with very heavy currents and heavy bars this loss may be appreciable in some machines.

Finally, we have some losses which seem to me rather important, and which exist even with ideal commutation. The paper mentions that commutation losses exist if the commutation is not perfect. These losses are important, but even if the commutation is perfect, the current direction in the armature changes; in other words, the current in the armature conductor is alternating current, and we know very well that in alternating machines, with heavy conductors, the losses in the conductors are rather large. There is no reason why we should not have the same losses in the armature conductors of direct-current machines. These losses are due to the fact that the current sets up fluxes across the slot and these fluxes reverse when the coil passes the commutator zone, thereby inducing voltage and consequent eddy currents. Then we have certain losses in the armature conductors under the pole tips, in case the saturation in the teeth is very high. This is due to the fact that the reluctance of the teeth just under the pole is very high, while the reluctance of the teeth next to the pole, with small saturation, is rather low. The difference will cause a certain flux to pass

across the slot, and since this is a changing flux there will be eddy losses. These losses were mentioned this morning. Finally we have the losses in the bands and coils.

It can be seen, with such a variation of losses, that it would be hardly fair to assume that the stray losses are similar in all machines, and I think that an attempt should be made to get at these losses separately. This, of course, can only be done by building machines which have only one of these losses at a time to any appreciable amount, and making tests along that direction.

In connection with commutator machines, it seems important for us to consider not only the direct-current commutator machines, but also the single-phase and three-phase commutator machines, for standardization. Some work along this line is especially desirable, because certain losses cannot very readily be tested in case of alternating-current motors, and in order to avoid complications it is always good to have some rules as to how they should be taken into account, when ideal methods of testing are not known. While the influence of the field distortion in the single-phase motor is usually not so important as in the direct-current machine, we have other losses. For instance, we have alternating current in all windings and consequent losses, and also the conditions are rather complicated due to the fact that there is a main flux and a cross or transformer flux. Since it is impossible to get a combination of the two fluxes as they actually exist, without having the load on the machine, there is at the present time no method of testing the core losses at all.

W. J. Foster: The two papers which I wish to discuss are those by Messrs. Olin and Henderson and by Messrs. Foster and Knowlton. The first contains diagrams showing connections of machines that must be considered in connection with the second paper, as that is not as complete as it should be. Now, reference was made this afternoon to the "circulating energy" method which was advocated by Messrs. Olin and Henderson, as a safe, reliable and accurate method, and a practicable one, where two identical alternating-current generators or motors are available. By referring to their paper, you will find a diagram given for connecting together two alternators for an input-output test. It consists in placing the machines back to back, with a coupling so arranged as to give an angle in one direction for one machine, and in the other direction for the other machine, and so that they will operate as generator and motor under certain conditions of load and power factor, and any conditions of load and power factor may be obtained by changing this adjustment. There is a direct-connected motor, preferably a direct-current motor, such as would be used in determining core losses or the friction and windage. It is not necessary to have the motor direct-connected, as it can just as well be belted.

The determination of load losses by this method, I have found, by a number of tests, involves no more difficulty, and is just as

accurate as the determination of windage or core losses by the same method. The only objection that might be made to it, possibly, is that one machine is operating as a generator and the other as a motor, and we must assume that practically the same effect is obtained in the motor as in the generator in the matter of the additional losses due to the presence of the current in the primary. In working up the results, the open-circuit core loss in the generator is taken at the normal voltage, plus the IR drop, and in the motor, the normal voltage minus the IR drop. That method is compared by Messrs. Foster and Knowlton as to the results obtained with two or three other methods that were tried. One of the other methods that the authors undertook with considerable confidence that it would prove the practicable one, was the no-load phase characteristic, for the reason that when an alternator is running with a very weak field, or very strong field, just so as to have full-load current in the armature at the normal voltage, it seems probable that the same conditions exist, as far as producing the stray load losses are concerned, as under normal load. The trouble with that method is the measurements which must be made by wattmeters, first with the lagging current, and then with the leading current, and that the results must be compared with another value that is almost as great, namely, that obtained at the minimum current input. There are many little errors in the readings when you are reading a comparatively large quantity, which may amount to a very decided error when considered with reference to a small quantity that is the difference of two large quantities. All such errors are eliminated in the "circulating energy method."

This particular method of "circulating energy" must not be confused with a form of operation in testing that consists of coupling together two alternating-current generators or motors in phase, supplying the necessary energy to run them from a third generator, and obtaining the current desired by adjustment of excitation. In this method we do not obtain the correct conditions of potential, field excitation, etc., whereas in the one I have just described all conditions are normal, and there is just that one difference between the machines, that one is a motor and the other a generator.

The authors have given a great many data, these data having been available and having been selected out of a great mass of data of tests made on machines extending back for fifteen years. We do not have data available on this new method, because it has not been in use. The data given in these tables were available because the Institute has had a rule that for what it has called load losses, a short-circuited core loss should be determined, and one-third of that taken. By referring to these tables you will see that in some cases the second column under "core losses" shows in certain cases the short-circuited core loss to be as great as 1.5 per cent of the full-load energy of the machine, and would affect its efficiency 1.5 per cent, and that in certain cases the

short-circuit core loss is greater than the I^2R loss, and in certain other cases greater than the open-circuited core loss, and in some greater than either; but by taking one-third of that, it will reduce the efficiency from one-quarter to one-half per cent, but you will also notice that the general average of all the machines is rather low, something like one-half of one per cent; and when we take one-third of that, it amounts to only one-sixth of one per cent, so that the machines have not been badly punished in the past, you may say, where the efficiency has been determined by taking into consideration one-third of the short-circuited core loss.

The input-output method was not tried on any one of these three machines, but, in connection with other machines tests were made by the input-output method, as has been referred to by other speakers. Such tests involve great difficulty and do not inspire confidence, since the tests obtained at different times by different men give such widely different results; whereas, with the "circulating energy" method, the results agree with one another every time you make the test, as closely as they do in the open-circuited core losses or determination of windage.

A speaker this afternoon referred to some of the machines given in the tabulation, as having very low short-circuited loss, and that it was unfortunate that machines had not been selected that had high short-circuited loss. We feel the same way, but there did not seem to be available any machine that had a high short-circuited core loss, and, therefore, we ran one of these machines single-phase, and greatly to our surprise, the loss there loomed up large, as you will see by referring to Fig. 11 of Foster and Knowlton's paper. Comparing Fig. 11 with Fig. 9, which refers to the same machine, you see that the short-circuited loss amounts to 3 per cent of the single-phase rating of the machine; whereas, when operating three-phase, it amounts to a little less than one-half per cent.

What we wish to suggest to the Standards Committee is that they do not discard these short-circuited core losses until further data are accumulated, as we think it probable that the entire short-circuited core loss should be taken. Another evidence that we have that the entire short-circuited core loss should be taken is what we have obtained from the heating of the machines. There are now available a great many data on the enclosed type of machines, not only steam turbine generators but water-wheel generators. It is a comparatively easy matter to measure the temperature rise of the air passing through the machine, when it is operating under load; then run the machine on open-circuit at over-voltage at a point where the losses are equal to the combined segregated losses as determined by the ordinary method. The difference in the temperature rise of the ventilating air under the two conditions is the measure of the load losses.

F. D. Newbury: The question before the meeting is not whether all losses should be taken into account in determining

the efficiency, but the best method of determining the true efficiency. The operating engineer can have no legitimate objection to any method that takes all losses into account, whether that method is based on the determination of the separate losses, or on the direct measurement of input and output.

Mr. Robinson's paper shows the difficulty, if not the impossibility, of obtaining an accurate, true efficiency by the direct measurement of input and output, even in the most favorable case, where both can be measured electrically. Even with his well-known ability and unexampled facilities, the extra load losses are very elusive. The load losses as shown in curves 1 and 3 depart markedly from the known law of their variation with load. The reasons for this are well brought out in the paper by Messrs. Chute and Bradshaw. One probable reason for the obviously incorrect results shown in curve No. 3 is the unusually high efficiency of this set. With a combined efficiency at full load of 91.3 per cent by separate losses, the efficiencies of the separate machines would have to be 97 per cent for the alternating-current motor and 94.5 per cent for each 500-kw. direct-current generator. These are unusually high efficiencies for machines of this class. The combined efficiency of 88.7 per cent in the 1000-kw., 250-volt set more nearly represents commercial figures.

If the correctness of this statement be granted, then it follows that more accurate efficiencies will be obtained from the separate loss method (including all losses) than by the most careful input-output tests.

Alternating-Current Machines. Three recommendations for estimation of extra load losses are made:

1. That open-circuit core loss and calculated I^2R loss be increased by a factor 1.1 to cover the extra load losses.
2. That the measured short-circuit load loss be taken as the load loss.
3. That one-half measured short-circuit load loss be taken as the load loss.

The relation between the load losses measured under short-circuit conditions and those existing under actual load is too complicated to permit any general statement to be made that will apply to all generators. Consequently, it is very difficult to make one rule apply to all machines. Load losses may be roughly divided into three classes:

1. Increase in armature core loss due to change in flux distribution.
2. Eddy and hysteresis losses in adjacent metal parts due to the stray field from armature current.
3. Eddy current loss in the copper conductors.

In generators having well-divided armature conductors and small flux per pole (including all small generators and all engine type generators) the load losses are, undoubtedly, mainly due to

flux distortion. For example, the 150-kv-a., 900-rev. per min. generator referred to by Olin and Henderson; the measured load loss for one generator at full load was 0.61 kw. and at $1\frac{1}{4}$ load 1.55 kw. The measured short-circuit loss (including I^2R loss) is 2.3 kw. at normal load amperes and 3.7 kw. at $1\frac{1}{4}$ normal load amperes. The I^2R loss calculated by Olin and Henderson is 2.27 kw. at full load and 3.55 kw. at $1\frac{1}{4}$ load. The measured short-circuit load loss is, therefore, practically zero at full load and 0.15 kw. at $1\frac{1}{4}$ load. The calculated I^2R loss is based on an assumed temperature which may or may not have existed during the short-circuit test, as pointed out by Brainard. Comparing the measured load losses at full load with the load losses at short circuit, the actual load losses at full load are seen to be greatly in excess of those at short circuit. The difference is, undoubtedly, due to the increased tooth loss under load, due to armature reaction. This same increase in measured load loss at full load over the corresponding loss at short circuit is shown in the 110-kv-a., 900-rev. per min. generator referred to by Foster and Knowlton.

In large medium-speed generators involving moderate flux per pole, the load losses are probably due to flux distribution and to increased stray field.

In high-speed steam and water turbine generators, the load losses are a combination of all three classes.

Single-phase generators are in a class by themselves, due to the pulsating armature field in distinction to the rotating armature field existing in polyphase generators.

I believe that a combination of the correcting factor advocated by Olin and Henderson and the direct measurement of load losses at short circuit advocated by Foster and Knowlton will be necessary. Moreover, different correcting factors will be necessary for different frequencies and for single-phase generators. The correcting factor is undoubtedly nearer the truth with small moderate-speed machines and low-speed engine type machines. For large moderate-speed and all turbo-generators, the actual load losses are probably equal to the measured losses at short circuit, judging from the data submitted by Foster and Knowlton. For single-phase generators, obviously the measured short-circuit losses are nearer the true load losses than those obtained by a factor based on polyphase machines. I agree with Mr. Foster that we should measure the load losses directly by the "circulating power" method. That method, however, is greatly limited by the fact that two duplicate generators are necessary, and it is an expensive test to make, so that it can only be used where the size of the machine and importance of exact efficiency demands that care and expense in the testing work. In spite of the complicated relation existing between actual load and short-circuit conditions, it is interesting to note the close agreement between load losses calculated by the two methods as presented by Mr. Knowlton in his discussion. It is also interesting to note that the load losses by any

method of calculation are small when expressed as per cent of the machine output. In 25-cycle generators, the average is well under one-half per cent, and in 60-cycle generators the average is well under three-fourths per cent.

Direct-Current Machines. Comparing the Olin-Henderson paper and the Erben-Page paper, the results are seen to be in fairly close agreement for the 470-h.p., direct-current commutating pole motor in the former paper and the 500-kw., 720-rev. per min. commutating pole generator in the latter paper. The correction factor for the 470-h.p. motor is 1.27 at full load, while it is 1.29 for the 500-kw. generator at full load; while at $1\frac{1}{2}$ load the former is 1.37 for both machines. In both machines the load losses are very closely proportional to the square of the load.

The non-commutating pole machines follow an entirely different law in regard to the variation of load losses with load, and the same constants cannot be applied to both classes of machines, particularly at light load. Other factors undoubtedly must be used for other classes of machinery.

To conclude:

1. Efficiency will be most accurately determined from the separate measurement of losses, including the extra load losses.

2. The extra load losses may be determined in the case of all machines by direct test when two duplicate machines are available and the importance of the matter warrants the testing expense.

3. They may be determined approximately in synchronous machines by established correcting factors and by the measurements at short circuit. I agree with Mr. Foster that we should not abandon the measurement at short circuit, because whether that does or does not represent full-load conditions, it is certainly a very good indication, and will detect faulty machines, particularly when the extra load loss is an eddy loss in the copper, which is a factor not always foreseen.

4. They may be determined approximately in commutating machines by established correcting factors. Correcting factors will vary with the ratio of no-load and full-load maximum inductions, which may be approximately calculated. That difference in the ratio is well brought out by the different conditions existing in constant-speed machines and variable-speed machines, and the reason for the difference in the correcting factors which Mr. Erben mentioned this afternoon.

5. The determination of additional load losses may be made only within relatively wide limits without causing a variation in efficiency greater than the minimum variation obtained with an accurate input-output test.

E. F. Collins: To those who have not had long and close contact with electrical testing, it may seem that input-output methods are best to adhere to, and that all this discussion concerning the stray load losses, brush friction, contact loss of

brushes, etc., should cease. On the other hand, one who has conducted many input-output tests knows that only by the most careful arrangement can correct efficiencies be secured through the use of this method. This includes the best of power conditions, as regards its freedom from fluctuations, and skilled men as observers. Sometimes as many as 20 observers are required to obtain simultaneous observations in a single efficiency test. In order to secure the same accuracy in efficiency determinations very much less error in observations is allowable than where losses alone are being observed directly. Many sets of observations must be taken, so that the probable error will be reasonable. The computation of these observations requires the very greatest attention and diligence on the part of the calculator on account of their multiplicity. Many meters of precision must be used. Heavy currents usually associate themselves with the method, especially in the larger units, and much care and judgment must be exercised to protect against unknown influence of stray fields. Thus one could continue to enumerate, almost indefinitely, precautions which accompany a successful determination of efficiency by input-output methods. Many such sources of error do not exist in using no-load methods, and where they do exist they do not influence final results to the same extent.

Mr. Robinson has shown well by tables and curves what may be done in determining efficiency by input-output methods. He has indicated somewhat the price paid for his results, and this price may be now and then justified. In general testing, however, I think there is little justification for the input-output method.

It has been said this afternoon that if we are to get at the true efficiency by segregated losses, we should include all losses. I agree that we ought to have approved methods of test which will allow of a determination of all losses, as well as a segregation of of such losses when required. I believe that certain methods exist and have been employed that do determine such losses, at least for certain classes of apparatus, such as direct-current rotating apparatus and alternating-current synchronous apparatus.

At the present time, standard methods exist for determining core loss with brushes at electrical neutral. Measurement can readily be made of bearing friction and windage, also brush friction, at no-load. The I^2R loss of the armature and fields may be readily and accurately figured for any load. The contact and brush resistance may be calculated from the contact loss curves, or it may be measured directly under operating conditions, as I will indicate later. Having determined these losses by no-load methods, the question naturally arises whether or not all the load losses are accounted for.

A method which may be relied upon to answer this question for alternating-current synchronous apparatus is the "circulating energy" method described by Messrs. Foster and Knowlton.

The objection to this method is that it involves two duplicate machines. As to its accuracy, however, in accounting for all losses, there is no doubt. It is, of course, desirable to have a method which may be applied with the same accuracy to single machines. Hence, the turning to a consideration of the short-circuit core loss as compared to the stray load loss measured by the circulating method.

I want to refer to the diagram given in Mr. Robinson's discussion, to illustrate that an equally efficient method has been employed for direct determination of stray load losses in direct-current machines. Incidental to this method of determining stray losses, and in view of the discussion this afternoon of brush losses, I want to point out to you that in this method we have actually measured the brush contact I^2R loss under operating conditions, through the use of insulated brushes, as shown. It may be of interest to say that a number of such determinations have been made in this way and they agree closely with standard curves of contact resistance loss that have been derived from tests upon a dead commutator.

I want to call attention also to the fact that if a change in brush friction occurs under load, this method takes account of it. From such tests I have had indications of change of brush friction with current. Some of those discussing the subject this afternoon held the opinion that this friction decreased with current, others that it increased. I am sure from the tests I have made that both are in a measure correct. In some cases I have observed an increase with current, in others an indication of a decrease with current.

It will no doubt require much investigation before practical methods may be devised that will permit of ready use for determining stray load losses for all classes of apparatus. In the meantime, perhaps, the use of certain empirical constants may be necessary in determining true efficiency by segregated loss method. In that event, however, I believe that some such direct method of measurement of these stray load losses should be employed as a basis for the value of such stray load losses, and correcting factors, should identify them with the designs with which they correspond.

B. G. Lamme: I wish to speak on the subject of load losses from the standpoint of a designer, and not as a member of the Standards Committee. Since I first looked over the Institute rules, I have always objected to the methods given in these rules for the determination of load losses, and also the method for determining efficiency, as it was an approximation that did not represent the facts closely enough to suit me.

Now, in comparing any of the methods of making tests for the stray losses, we should not take good machines when making such comparisons, because, in well-proportioned machines, the extra losses may be relatively low. We should pick out machines which we have reason to think have abnormal extra losses, and

in that way we may find so large an extra loss that errors in the determination are of smaller proportion.

For many years I have been concerned in the measurement of load losses, and have frequently taken up the calculation of them just to determine the possibilities for the application of correcting factors, which would cover fairly accurately the extra losses. Such calculation is a long and complicated process in many cases, but when carefully carried out, I obtained some astonishingly close results in those cases where I had reasonably accurate data to compare with, but I will say that the accuracy of these results was, in one way, very discouraging; for in some cases, the larger items in these calculated extra losses were such that they apparently bore no relation whatever to the measurable quantities; that is, the data we could obtain by any simple direct measurement had no relation to the extra losses, and therefore our separate measurement of losses gave no direct quantitative indication of the value of these extra losses.

In a very well proportioned machine, I will venture to say this—that I can review the design of that machine, and I can then estimate, off-hand, the load losses as closely as they would be given by any of the methods suggested this evening. Still, these methods may show closer, on individual items of extra loss, yet, in my rough estimate, I would allow for some losses not touched on at all by any of the methods proposed for approximating the extra losses. In taking any of these methods of approximating the losses, you may get results which look very good from the general standpoint, but if you look at the results closely from the design standpoint, you are likely to see something in them that you know is inconsistent with the design—and that throws doubt on the whole result.

Take the method of determining losses by short circuit. In many machines there are extra losses due to saturation of certain parts of the circuit, and these do not appear at all in the short-circuit test, and therefore, in such cases, it is purely an accident if the measured short-circuit loss happens to coincide with the extra losses in the machine.

It looks to me as if all of these methods, including the input-output, under commercial conditions, must be considered as only rough approximations. I have seen a good deal of testing done by the input-output method, and I have never been satisfied with the results unless I knew beforehand what the extra losses ought to be. I have seen tests repeated four or five times until the results happened to give a value that everybody agreed upon as being reasonably correct, but in fact, this particular result may not have been any closer than any of the others. It seems to be largely a question of keeping up the testing until everybody is satisfied or tired out. That is how much confidence I have in it.

We must look at this input-output testing from two different standpoints. The man who tests the machine from the instrument

standpoint may have absolute confidence in the instruments and in the men who make the tests for him, but the result which he thinks is satisfactory or correct may appear to be decidedly incorrect to the man who designs the machines, for he may know that the stray losses indicated are inconsistent with his design.

It is possible that some correction factor, even if an assumed one, is better than to do away with any allowance for the extra losses. The great trouble with the old rule of segregated losses was that the engineering public knew that these did not represent the total losses, and did not want to accept the resulting efficiencies, because there was something left out. Now, the total extra loss usually represents only a small value compared with the measurable losses, and even if omitted, the error is ordinarily rather small, although, in extreme cases or under very special conditions, it may become quite appreciable. In some cases, this omission of the load losses has been made up by the direct assumption of a certain per cent reduction in the efficiency, as, for instance, one per cent. Such assumption unquestionably averages closer to the true result than omitting the stray losses altogether. But it seems to me that this is largely a commercial consideration, and, from an engineering standpoint, all we can do is to state what the measurable losses are, and then possibly indicate roughly the total extra losses, but not make them the subject of any guarantee, as we should not guarantee what we cannot measure.

H. F. T. Erben: I wish to say a few words in relation to the possibility of obtaining a correction factor which will be universally applicable to machines of a given type.

I note in Messrs. Olin and Henderson's paper that they recommend certain correction factors, each of which will be applicable to all machines of a certain class. For example, they have a correction factor of 1.3 for direct-current generators and motors; 1.1 for alternating-current generators and synchronous motors; 1.1 for 60-cycle converters, and 1.0 for 25-cycle synchronous converters.

Our tests have shown that different correction factors must be applied to various types of machines comprising a general group, and these factors will vary very considerably. For example, we have shown that the correction factor for a fully compensated generator may be as low as 1.2, for a commutating pole generator about 1.3, and for a non-commutating pole generator it may be as high as 1.5. Again, the correction factor for variable-speed motors will be greater than for a constant-speed motor, due to the distortion of the wave form.

There will also be a different correction factor for commutating pole and non-commutating pole synchronous converters and another correction factor for converters of the synchronous booster commutating pole type. It is therefore evident, that if we intend to apply correction fac-

tors we must subdivide any given class of apparatus into its various types in order that we may arrive at the true value of the efficiency. Such a course of procedure might lead to such a multiplicity of correction factors that the whole scheme would become unworkable. However, I am not saying this in any spirit of discouragement, as I believe the various manufacturers should continue the tests which have been so ably carried out during the past few months, and it might be advisable later on for the Institute to appoint a sub-committee to formulate rules based on all the available test data.

I fully believe that, in those cases in which it is impossible to obtain accurate input-output tests, the efficiency should be determined by following the segregated loss method in combination with a suitable correction factor.

B. A. Behrend: All of us who have listened to the thoughtful remarks of Mr. Foster will, I think, be inclined to agree with him absolutely in his statements and recommendations. As I understand Mr. Foster, he desires to represent the full efficiency in his tests, and he suggested for alternating-current generators, of course, also for direct-current generators, the input-output test, which was first suggested in 1885, by the late Dr. John Hopkinson. The cost of that test is, however, frequently prohibitive. On that account it is difficult to carry it out in the power house or in the testing department. From time to time, however, two generators happen to be on the same shaft, either alternating-current generators, or direct-current generators, and then such tests can be made in a very simple and accurate manner, yielding very important data.

In applying these data to other cases, by using the experienced designer's judgment, we can obtain fairly good ideas of the actual efficiencies of machines, which can be used to form a basis for guarantees, even though, perhaps, we know only the individual losses. For example, if we have to guarantee a 25,000-kw. turbo-generator, to operate at 1500 rev. per min., and we have the data on a 10,000-kw. unit, it would not be difficult for a man of Mr. Lamme's experience to make his estimates in such a manner that he would secure fairly accurate results.

The advantage of the use of the short-circuit loss curve, I think, is not to be underestimated. The use of one-third of the total loss is arbitrary and absurd, as Mr. Lamme justly pointed out. Whether or not we shall take the entire short-circuit loss or whether we shall deduct from it the core loss, corresponding to the open-circuit voltage, which corresponds to the short-circuit current, is a matter of judgment.

Mr. Erben's extremely interesting results have shown that in order to coordinate the data on different types of machines it will be necessary to use correction factors, "thousands of them," and we should be worse off at the end than we were at the beginning.

If we should deduct the iron losses from the short-circuit core losses, we would certainly get a more nearly accurate measure

of the short-circuit losses than we should have if we included the obvious iron loss in the amount that we use for the correction. The philosophy, I believe, of this whole thing, comes right down to this—that the further our experience carries us, the more we doubt. Those of us who have been through the building of large machines up to 25,000 kw., at very high speeds, appreciate the fact that we continually learn. As Darwin said in the preface to his great work, "The Descent of Man," "It is more frequently ignorance that begets confidence than does knowledge." It will serve no good purpose to collect a number of utterly worthless correction factors. It is senseless to do it. You had better take the data Mr. Schuler mentioned today, calculate conventional efficiencies, and thus simplify your work. Conditions are constantly changing. You all remember that ten years ago the former Grand Central Station was completed. To-day that station has disappeared, and a new one, which has taken its place, has just been opened. Ten years ago the large 5000-kw. generators which Mr. Lamme designed for the Manhattan Railway in New York City were the leading machines of their class. To-day they are thinking of replacing them with turbo-generators. In ten years we have gone from 75 rev. at 5000 kw. to 1500 rev. at 25,000 kw.

I want to point out again that you are standardizing the past. Probably five years hence the facts will have ruthlessly wiped away the whole cobweb of rules we are laying down here. Your rules must be flexible, so that they can be applied to changing conditions. I plead for this because I feel very keenly the hampering influence of the old rules. It is a matter well worthy of serious consideration, especially by designing engineers. I know Mr. Lamme is in full accord with me. I do not like to say that for him, because he can say it for himself. I am sure I am in full accord with his ideas on the subject. It is extremely dangerous to go too far. The problem before us consists in laying down a few general rules which will not handicap and hamper the designing or consulting engineers. Make the rules general, and prescribe methods of test. For example, say whether the commutator should be seasoned at the factory or outside. If you do not want to say it should be seasoned at the factory, say it should be seasoned outside of the factory; if you do not want to say it should be seasoned outside of the factory, make such provision as you think is proper, but it is most important to do this, and to say what you want.

W. J. Foster: I want to say another word on the matter of the short-circuited core loss. I should hate very much to see correction factors adopted, one-quarter per cent, one-half per cent, or any per cent, that would punish good machines to the advantage of inferior machines. I should prefer to see the entire short-circuited core loss taken, in order that we might proceed at once to reduce these losses. It can be done in nearly every case by better design, and that is what we all want.

The use of ½ the short-circuit loss probably does not approximate the correct quantity that should be added. I think we should take the whole loss, and possibly a little more, rather than a little less. Mr. Behrend will excuse me for pointing out that, unfortunately, the other scheme to which he referred would result in boosting the efficiency of two-thirds of the commercial machines at the present time, for the reason that the excitation that is required to put the short-circuit current through, gives an open circuit, a higher core loss than the entire short-circuited loss on most machines, and, therefore, when you subtract it, you get a negative value, and if you add that negative value to the other losses, you will have your efficiency raised rather than reduced.

B. A. Behrend: I meant to correct the exciting current for the armature reaction. I did not want to go into that detail.

W. J. Foster: Just the reactive drop?

B. A. Behrend: Simply take the reactive drop. I took it for granted that should be taken into consideration.

W. J. Foster: In line with Mr. Lamme's suggestion of correcting the core loss, or the combined loss and I^2R, I have never succeeded in getting anything that was reasonable or that fitted the case; I trust that some positive evidence will be brought forward that the entire short-circuited core loss is the wrong thing to take. We will probably have to wait until some one has a pair of identical machines to test by the "circulating energy" method, which we appear to agree on, and on those same machines have the short-circuited test applied, and find the case where the correction as determined by the short-circuited loss is going to appear absurd when compared with the actual stray load loss, and then we will have some direct evidence.

As stated before, I regret that the particular machines that were available for use in Foster and Knowlton's tests all proved to have small short-circuited losses, as polyphase machines, but does it not seem significant that one of these has very large short-circuit losses as a single-phase machine, and that these losses agree very closely with the load losses as determined? There have been a number of cases in the past with which I have had to do, of single-phase machines, where changes were made after the first tests, in order to reduce temperatures, in connection with which the short-circuit losses were reduced.

Therefore, I consider that the evidence presented by the curves, Figs. 9, 10 and 11, of the paper by Foster and Knowlton, should be taken up and carefully considered by the Standards Committee, and something in the way of positive evidence to condemn them should be obtained before they are rejected entirely.

James Burke: The papers under discussion and the corrective factors introduced should not, perhaps, apply only to the machines, but also to the instruments and to the men, and I think that these tests show that instrument designing is in the same high class as dynamo and motor designing, they show such

close agreement with what might be expected from dynamo and motor tests.

It seems to me that the function of the Standards Committee is to standardize and not to average. The suggestions throughout these papers for corrective factors is to average these factors, and that eliminates the individuality of the designing. Now, it is quite possible, and I think most designers will agree on this point, to have negative corrective factors. For example, if we take a direct-current generator and shape the pole pieces with varying air gap so that the distribution of flux is approximately a sine wave under load, which would be quite different free, then our load core losses are less than our free core losses. That is not only a theory, but I have proved that by tests. I know that some European machines have been built that way, in which the air gap is so proportioned that the influence of the armature reaction is such as to produce very nearly a sine wave under load. Now, if a designer introduces such a feature as that, that is a negative corrective factor, he gets no credit for it, and his individuality is removed as soon as the Standards Committee averages these factors. The question of compensated machines, the difference between the 60 per cent compensated machine, which Mr. Erben has referred to, and the 100 per cent compensated machine, would have to be taken into consideration by the Standards Committee, or the punishment due to the average law would apply. In the compensated machine we may have large corrective factors, depending on the distribution of the compensating conductors. If you have two or three compensating conductors per pole, you probably will have quite a different increase in loss under load than when you have a larger number.

To do any good, to get any reasonable consideration for corrective factors, the Standards Committee would have to tabulate on the alternating-current end of motor-generators a great many construction details, whether the slots are closed, or open, or partly closed, the depth of conductors, many factors of that kind, to determine the corrective factors for the alternating-current end, and similar treatment on the direct-current end. Then you would have to introduce factors covering the way that the brush losses were determined—I think we have heard this afternoon that there are a good many different theories on brush losses and different opinions as to the amount of brush losses. Now when it is all finished, all that we have accomplished is the recognition that there may be, and it is to be expected that there will be, some corrective factors on account of loads, but I do not think we have any idea as to how much they should be. Personally, I have conducted a number of tests in which I have found so little corrective factor that I could not say I had found any, and in every case there has been a large difference. I am making a plea to avoid the averaging of these corrective factors and to leave some room for individual effort in telling the story of the individuality of different types of machines.

Charles P. Steinmetz: I can see a hard time ahead for Mr. Lamme and myself as members of the Sub-Committee on Revision when we attempt to designate the exact methods of determining the stray load losses so as to give the operating engineer the exact and true efficiency which he wishes to have, and which the input-output method, as I understand, is incapable of supplying, and which you cannot get by considering the short-circuited core loss, or open-circuited core loss, or any other thing, except by using correction factors, and as many different correction factors as you build machines. Our only hope is that we shall be assisted by the engineers who are now interested in the stray losses, by constructive criticism; that is, when we have drafted a tentative rule we shall submit it to them, and in case of their disagreeing with us in our first attempt, we hope they will send us material for the formulation of a better rule.

In regard to the short-circuit core loss, as shown in the diagram which Mr. Behrend discussed, I wish to say that ½ of the short-circuit core loss was not a mere incident, and while at present the data seem to show that the total short-circuit loss is more correct, we must realize that when the rule was made we had different machines to deal with. The single-phase low-speed alternator was a very common machine then, also other types of machines which we rarely see now, such as the inductor alternator, where the field exciting winding was far away from the armature, separated by solid magnetic material. In these machines the pulsation of single-phase armature reaction reached back throughout the entire field when you ran at the low densities corresponding to the short-circuited core loss; while at the rated voltage, especially in a highly saturated machine such as the inductor alternator, the pulsation due to the single-phase armature reaction is very much less, and we knew, if we used the full short-circuit core loss, there could not be a loss of any such magnitude because the machine would have burnt out in less than no time, and therefore, especially since people were rather horrified when we made the first test of that character, and found these apparently enormous losses, we had to play safe and use a value which we knew was less than the probable true value. However, we were proceeding in the right direction to the extent that instead of neglecting the short-circuit loss altogether, we at least took in a part of it.

Now, the short-circuit loss undoubtedly gives some indication. The residual loss after deducting the armature I^2R loss and the iron loss corresponding to the approximate magnetic density under short-circuit tests, affords an excellent criterion as to the extent of the stray losses at full load. Even if in some cases it leads to ascribing to the machine an efficiency lower than is actually obtained, nevertheless the general adoption of the plan of taking this residual short-circuit loss as a measure of the stray loss at full load, would provide designers with a criterion which would lead to designs of improved quality.

E. M. Olin: Although Mr. Robinson, in drawing his conclusions, in his paper, states that the input-output method of measuring efficiency is "one that can be considered only in connection with special investigations" and "as a check method for demonstrating the reliability of other methods better suited to commercial needs," it is a fact, I think, that a reading of this paper would lead the average engineer, inexperienced in this class of work, to believe that this method is perfectly simple and thoroughly reliable for measuring the efficiency of rotating electric machines. Such a conclusion is so at variance with the experiences of the writer and a number of engineers with whom he has been associated, extending over a number of years, that it seems advisable to point out a few contributing factors not taken into account by Mr. Robinson.

In propounding the mathematical theory which deals with "indeterminate errors" and the average deviation of the mean reading from the true value, for the purpose of illustration, use is often made of an example like the following: A skilled marksman fires a thousand shots at a target under conditions as nearly alike as possible. Experience shows that the shots will be distributed in a manner which at first sight seems entirely irregular, but which, on more careful examination, will be found to be approximately in conformity with a perfectly definite law, the law of chance. The plus and minus deviations of the shots from lines drawn at right angles through the center of the target are about equally frequent, and small deviations occur with much greater frequency than large ones.

It can be shown mathematically that there is a certain definite curve, representing the law of chance, whose equation can be expressed in symbols, and that the average deviation of the mean is as shown by Mr. Robinson.

Now, in this example of the marksman firing at a target which I have just cited, it should be borne in mind that the target is fixed, not swinging.

In input-output tests the mark at which we are firing is the true value of efficiency. However, the true value of efficiency is the ratio of the output as determined from measuring instruments in the output side to the input as determined from certain other measuring instruments in the input side. In other words, during our observations we have two targets and two marksmen or sets of marksmen.

Now if the output is constant for all readings, the target remains fixed, and it would be correct to figure the input and output separately according to Mr. Robinson's method but not the efficiency direct from each observation or set of observations.

In the tests described, however, the output is not constant. In Table II, the output ranges from 470 kw. to 512 kw., a variation of some 40 kw. The target at which the marksmen are firing, then, instead of being fixed, is swinging.

Now the instruments used in the incoming circuits of motor-

generators, such as are covered by Mr. Robinson in these data, do not swing synchronously with those in the outgoing circuits, due to the different types of damping used in the various instruments, the introduction of series transformers, etc. This introduces another complication in figuring tests such as described in this paper. The target which should be fixed is not only swinging, but swinging along an irregular curve with a varying time constant. Obviously, the problem is not quite so simple as one might be led to believe from glancing over this paper. It is undoubtedly true, as stated by Mr. Robinson, that certain of the no-load losses may change during the progress of the input-output tests. These should be measured carefully by the separate loss method and due allowance made, when computing efficiency, for such changes, and average values should be used for such factors as frictional losses in brushes and bearings and brush contact losses.

L. T. Robinson: I am willing to admit the extreme difficulty of satisfactory input-output testing, but not its impossibility. Mr. Newbury said that the test results obtained were not right because they departed from well-known laws. We have been all day yesterday and today discussing these well-known laws and there appears to be no definite understanding of them on which definite criticism of the results obtained could be based.

With regard to the shooting at the swinging target, I cannot see that this has any bearing, so long as the individual observations of the output are not far enough apart, so that the efficiency line that joins them does not depart substantially from a straight line. I do not recommend these methods for practical tests. I think that an impartial examination of the evidence presented will indicate that the results are correct within the limits stated. If you cannot look at it that with the input-output test we prove that the circulating loss tests are right, perhaps you will look at it the other way, and say that the circulating loss tests prove the input-output tests are right, because we got the same answer by both methods. After a full appreciation of the variability of the brush friction, etc., came to my notice, we made some more tests, and every point comes within the degree of precision claimed, and beyond which I did not care to go.

As to the No. 3 test in the paper, I think I made it quite clear that that was not very good, and I think the reasons given were quite sufficient. In a machine in which the brush friction is about one to 1.5 per cent of the total output, and with the statements this afternoon, by presumably competent observers, that brush friction varies 300 per cent, why is it any fault of the method or the test if the points do not fall all within the belt? I submit that the evidence is sufficient to establish all the claims made.

C. J. Fechheimer: In the paper by Messrs. Foster and Knowlton, on the last page they state "The phase characteristic method is faulty, due to the difficulty of obtaining accurate

wattmeter readings at the low power factors." If we have a three-phase circuit and use single-phase wattmeters and the power factor is less than 20 per cent, both wattmeters will indicate high values, although one wattmeter will read negative. The true power is the difference between the two wattmeter readings. Both wattmeters read with considerable acccuracy and the only inherent errors which are introduced are those due to observation, and the difficulty in obtaining with accuracy the difference between two nearly equal quantities. However, the error that we usually think of in connection with single-phase wattmeters when connected to low power factor circuits does not apply to the three-phase case with the standard two single-phase wattmeter method, because a single-phase wattmeter reads inaccurately when the current and electromotive force are nearly in quadrature, and this condition obtains when the power factor of the three-phase circuit is not far from 50 per cent.

It is our opinion that the phase characteristic method is the most accurate one for measuring the losses within the machine, with possibly the exception of the circulating energy method. This latter, however, can be used so seldom that we must resort to some other means, and usually the phase characteristic method can more frequently be employed, with the equipments in most test departments in manufacturing companies.

In regard to the modified segregated loss method, we believe that all of the short-circuit losses should be included instead of one-third of the short-circuit losses, and that the core loss should be taken at the internal voltage as given by the terminal voltage plus the impedance drop taken in the proper phase relations. The reactance of the armature winding may be measured with the rotor removed, the current being circulated at normal frequency in only one of the phases. The reactance thus determined may then be used for computing the internal voltage.

B. A. Behrend: In the papers that are before us the difficulty of measuring the power in watts or kilowatts has never been discussed. This is rather surprising. Mr. Robinson will appreciate the immense difficulty of obtaining correct wattmeter readings. I remember in the early days it used to be one of the most difficult problems, and the new instruments have by no means solved it. Even the best instruments for the purpose are influenced by the proximity of large currents circulating in cables and by magnetic fields which exist almost everywhere in the shops. Let us take a simple case, and endeavor to determine the power factor of an induction motor at different loads. I have had experience in that direction, and I have had working with me some of the learned professors of our great universities, and have found it necessary to correct power factors of 101 and 102 per cent, to harmonize them with reasonable facts. It is so important a matter that I believe it should not be omitted in our consideration of this complex subject.

I want to say that in a number of cases of high-tension circuits, I have found that the power factor of an induction motor was extremely low, due to the peculiar condenser effects in the shunt windings of the wattmeters. It is an effect which it is very hard to eliminate and very hard to correct. At low power factors this effect is tremendous. Of course, it can be corrected in the well-known academic way, if we care to pile assumption on assumption. This is a matter of importance. Mr. Robinson might give us his views of the accuracy of wattmeters and their use in alternating-current circuits in power houses and on the testing floor. I have personally no faith in them, and I am just as willing to take the no-load current of the induction motor and use the simple circle diagram developed by me in 1896, when stimulated by the difficulty of harmonizing the results of wattmeter measurements with the likely facts, in order to get an idea of the power factor.

L. T. Robinson: You may be interested in my views on what accuracy we can obtain with wattmeters in commercial testing. First we will take the wattmeter as it is, and then we will see how much influence the testing floor has on it. We can build wattmeters, and they are constructed and obtainable commercially, that will measure, with power factors down to 10 per cent, within about 2 per cent of the correct value. That 2 per cent is largely correctable. This refers, of course, to single-phase operation. But you can, I think, get the best results when you want a really close measurement on three-phase circuits at low power factor, by using three instruments, so that you do not have the trouble that you have in subtracting one reading from another, which, of course, when they are pretty near alike, is bound to introduce large errors. You can choose instruments that will go over the scale, perhaps with one-third of the product of the rated volts and amperes of the circuits, and use three, and get very good results. When you introduce larger quantities for volts and amperes you must, of necessity, employ instrument transformers. Now, the phase angle between the secondary current and the primary current in the current transformers is determined within, perhaps, three to five minutes of the equivalent angle, which again brings you substantially within the limits spoken of for the wattmeter alone. The total magnitude of that phase difference can be kept small enough so that correction is reliable.

With regard to the potential transformer, it is possible, practically, in ordinary work, to eliminate them altogether, because the usual transformer is so constructed that, with non-inductive load, at certain loads the phase displacement between primary and secondary voltages is zero, and you have only to find out what that load is and put it on in addition to the wattmeter potential coil to bring the angle to zero, and use it that way. How far that can be applied to the testing floor, I do not know. You have things to deal with there that are difficult to handle.

The difficulty is not great if you can retain the people permanently who have been shown how to do the work. I will admit the trouble in doing such work commercially, but when the real necessity for it arises, I do not think the instruments or the method will be found wanting.

B. A. Behrend: The disturbing effect in the neighborhood of the wattmeter is because the wattmeter is so apt to be influenced.

L. T. Robinson: I feel sure that the instruments to which I refer are entirely free from those disturbing effects.

Carl J. Fechheimer: I always understood that the wattmeter was incorrect, and the current in the measured coil is almost in quadrature with the current in the corresponding coil.

That only occurs at 50 per cent power factor, or approximately 50 per cent power factor.

L. T. Robinson: It does not occur at 50 per cent power factor when you use three instruments. The power factor on each instrument is the power factor of the whole circuit.

Carl J. Fechheimer: Will you have correct results on your two instruments when one wattmeter reads a negative value and the other reads a positive value?

L. T. Robinson: Incorrect, in comparison with the results obtained with three instruments.

Carl J. Fechheimer: Why?

L. T. Robinson: You are substracting one thing from another thing, to which it is very nearly equal, and a very small inaccuracy in the wattmeter becomes a large part of the difference which is shown.

Carl J. Fechheimer: Each wattmeter will read fairly correctly?

L. T. Robinson: Yes.

C. A. Adams: I will answer one part of Mr. Fechheimer's question. In the case of the two wattmeters three-phase power measurement with nearly 50 per cent power factor, where one wattmeter reads zero, or very nearly zero, the per cent error of the low reading wattmeter may be very large but the actual numerical error of the total measurement is exceedingly small, and quite as small as when both wattmetters read high.

James Burke: If I may be permitted to make a suggestion to the Standards Committee, it is that in preparing new rules, they should not overlook the introduction of the necessary rules for the correction of instruments when efficiency tests are made by input-output methods. We have heard quite a little on that this evening, and I think it is very important, since input-output methods do come up occasionally, that the Standards Committee tell us how to introduce corrections on wattmeters and on various other instruments that come into use, and also to correct for the nature of the voltage supplied, whether pure sine wave or a wave that has some other complications in it. I think that is going to be quite important, be-

cause, otherwise, input-output methods will be relied upon, without their proper correction factors, and it may be that the correction factors for input-output methods would be as large as on the summation of loss methods, and it is equally important not to overlook them.

B. A. Behrend: Mr. Burke's remarks should be endorsed emphatically and heartily by all of us. We must know how to correct instruments. I have never been able to get accurate readings in a testing department because of the effect of large magnetic fields around the instrument. You cannot shut down a large manufacturing plant, employing twenty thousand men, for the sake of making one test. Night testing and Sunday testing are equally unsatisfactory for other reasons. I want to know if wattmeters can be obtained commercially which are not readily influenced by outside currents and powerful magnetic fields.

L. T. Robinson: Yes.

J. L. Harper: We have heard a great deal of discussion as to corrective factors, and my remarks this afternoon have been referred to by Mr. Newbury as not being pertinent to the discussion, but as I understand it, the necessity for determining all these losses is for the purpose of arriving at efficiency. I do not wish to have it considered that any remarks of mine had reference to any special method of test, or to any test; I merely desired to protect true efficiency from the corruption of a commercial understanding of efficiency; and instead of applying so many corrective factors to the losses, why not apply one corrective factor to the efficiency?

Mr. Schüler spoke of using the word "conventional" efficiency in Germany—why not use "conventional" or "commercial" efficiency for what manufacturers are able to determine as efficiency? You all seem to agree that you can determine certain of these losses with fair accuracy. Why not decide upon these losses and set them apart and let them be determined, and call that a certain kind of efficiency, designate it by some kind of qualifying term that will differentiate it from the true efficiency, and eliminate the necessity for the use of these thousands of corrective factors? That also may assist Dr. Steinmetz in solving that very difficult problem of satisfying the operating engineer in getting the true efficiency, which you all seem to claim is a physical impossibility. That may be so at the present time, but as time goes on the distance that separates the losses that you are able to determine by the segregated loss method, from all losses, I think will decrease, and there will come a time when further characteristic losses will be added to the determinable ones, and the difference between true efficiency and "commercial" or "conventional" efficiency may be decreased. The present rules I believe to be inconsistent, in that they give a fairly clear definition of efficiency, and then say that efficiency may be determined by the measurement of the losses separately.

You have made it very clear to me that it is a physical impossibility to determine these losses separately. Therefore, this efficiency which the rule purports to approve, is not a true efficiency, but some qualifying efficiency which you may call "conventional" or "commercial."

I merely wish to make the suggestion that by incorporating this one corrective factor, (which may be $\pm X$) in the efficiency, you make unnecessary all of these thousands of other corrective factors, and thus simplify both the matters before you in discussing the losses, and also the work of the Standards Committee in endeavoring to satisfy all parties.

E. I. Chute: It is very true, as Mr. Behrend and Mr. Robbins brought out, that if we try to make constants to account for the additional load losses for all types and sizes of apparatus we will have constants as numerous as the sands of the sea. But the case is not as bad as that. There are not very many operating or consulting engineers complaining about the smaller types of apparatus; it is the larger types, where one per cent in efficiency counts in dollars and cents. In these the constants can be simmered down to comparatively few in number, as will be noted in the summary to the paper by Messrs. Olin and Henderson. It must not be thought that these constants are absolute, nor do they need to be. No method of test now in use, even with the help of the laws of chance and Mr. Robinson's shaded belt, will assure us of the true efficiency of a machine, within two or three tenths of one per cent. The additional load loss, being small in proportion to the total losses of any machine, may vary materially, often even 25 to 50 per cent, without affecting the actual efficiency more than a quarter of one per cent, so, even though the additional load losses may vary slightly in the various types of the larger machines, a large number of them may be bunched together under one classification. An average constant for such a classification, applied as suggested, will then give operating efficiencies as accurate as the average engineer demands.

The average input-output test is not acceptable to either the manufacturer or operator, and some other solution of the problem of determining true efficiencies within reasonable limits must be worked out. The sooner we make a start at it the better.

Mr. Robinson's paper serves to bring out very nicely the limitations of the input-output test, even when taken under the best conditions and the calculations made with all the refinements of mathematics. On one curve shown by a previous speaker, two values of efficiency are given at normal load, the difference apparently being due to the exchanging of one instrument for another of similar capacity and accuracy. It was noted that there was a difference between these values of four tenths of one per cent, a greater difference than accounted for in either test by any possible change in constant losses. Why

might not this discrepancy have been in just the opposite direction to that shown?

The values of additional load loss obtained in all the tables but IX, X and XI speak for themselves. If these values are correct, why all this agitation? The separate loss method of efficiency determination is good enough. If such results with the input-output method of test are obtained by Mr. Robinson with his reputation for refinement and accuracy, what can the rest of us hope for?

L. T. Robinson: There should be no misunderstanding on that point. The only claim I make is that these points will fall within that belt. And they do. The instruments were interchanged, at one point, and there is no conclusion to be drawn from the result except that the results are within one-quarter of one per cent, because the belt is only that wide and the points fell within the belt.

E. I. Chute: Other unaccounted-for inconsistencies in these tests might be pointed out, and it is my personal opinion that an accuracy of two tenths per cent claimed for them is not warranted. It only goes to show that even when the most elaborate and refined of methods are applied to the input-output tests, the results are very uncertain.

H. M. Hobart: No mention has yet been made of the best method of determining the true efficiency, the method which the Standards Committee would probably be well advised to adopt, and that is a method based on calorimetry. For instance, one can measure the losses at no-load with exactness, while a given quantity of air is being passed through the machine. The temperature of the air at the inlet and at the outlet can be taken. Again the machine can be run at full load and the same quantity of air measured at the inlet and outlet. This gives a simple way of deducing quite exactly the ratio of the losses at full load to the losses at no-load, and consequently of arriving at the magnitude of these stray losses, and consequently, also, of deducing the true efficiency. I believe that by these means we may arrive much more closely at the true efficiency than by any other practical method.

I allude first to large machines, because generally the conditions surrounding the contract for large machines are the more important, but in my opinion, for smaller machines calorimetry also offers the best method. In the case of a small machine, you can house it completely. You can house the motor in a case, through which you pump air, measuring the quantity of air, its inlet temperature and its outlet temperature. The measurement is made first with load. Then the measurement can be repeated at no-load with the addition of suitably disposed rheostats, into which you can introduce an additional loss, which will give you the same inlet and outlet temperature when your machine is running unloaded as was obtained in the first test when running it at its rated load. The amount of the losses

in these rheostats will be equal to the load losses, including therein the legitimate and the illegitimate load losses.

Another way is to have your machine in one receptacle and then let the air pass on to still another receptacle in which you have your rheostat, and get the temperature drop across each. It is a thermal-drop process. When the thermal drop across each receptacle is equal, then you know that the loss in the machine is equal to the loss in the rheostat. If the drop is not equal, you can get the loss by taking the ratio of the thermal drops. There is no need to measure the *quantity* of air, but merely to maintain the flow constant.

W. F. Dawson: The method proposed by Mr. Hobart is interesting and replete with possibilities, but it requires much study and care so that new sources of error are not introduced, greater than those contended with previously. The difficulties of successfully measuring the actual amount of air delivered, and charting it so as to get a true average, are very great. I have been recently checking up losses with the thermal capacity of the air passing. There is probably additional loss, by heat convection, that will not be measured by thermal capacity of the air passing through. In respect to turbo-alternators, and particularly those which are provided with definite air passages for inlet and outlet, it will be exceedingly instructive to make these tests and keep them for comparison and reference. I doubt very much if the consulting engineers and the customer will very rapidly embrace the facilities which Mr. Hobart has offered in respect to determining these load losses. Mr. Erben has shown splendidly how these load losses are affected by design. It would be a great mistake and an injustice for the committee to lay down any set of rules and say that "this class of machine shall be considered to have ¼ of 1 per cent additional loss" and "this class of machine shall be considered to have ½ of 1 per cent additional loss," etc., because it will handicap individual initiative. It will put the designer and the manufacturer of inferior machinery, to a certain extent, on the same basis as the designers and manufacturers of machines who have practically eliminated these load losses. I hope the discussions and investigations will go on. There cannot be any question but that this discussion will make for better designs of machines, smaller load losses, or a considerable elimination of them. Mr. Lamme pointed out, and Mr. Erben and Mr. Burke, and others, have also pointed out, that while we may indicate what these losses are, it is going to be an exceedingly difficult thing to standardize them.

H. M. Hobart: I do not propose to measure the quantity of air. That is difficult. We do not measure the quantity of current when we get the drop through two resistances. We keep the current constant. The air flow is kept constant by running the fan or blower at constant speed. There is nothing new in calorimetric methods.

B. G. Lamme: I have listened with a great deal of interest to what Mr. Harper has had to say on the question of load losses. He says that if we cannot measure all the losses, and will state what we can measure, and if we are willing to state the situation plainly, he is willing to accept it. If everybody else would agree with him in this, it would make it very easy for the Revision Committee. Mr. Harper called attention to putting a factor x in the equation. However, it has been suggested by others that such a correction factor puts a penalty on good design. That is true, but you must not forget that virtue is its own reward. The designer who builds with very small extra losses has a correspondingly better machine, because any reduction in such losses reduces the temperature, and therefore allows him correspondingly to increase the output. The designer who builds with high extra losses will eventually lose out, so that the normal tendency is toward the reduction of such extra losses.

Mr. Harper also stated that eventually we would come closer to the true efficiency. I agree with him, but possibly it will not be so much by improved means of measuring as by reduction in the extra losses. I know that, right now, the tendency toward reduction of the extra losses is very strong, and that all losses in the machines are being analyzed and studied very carefully with a view to getting better performance and larger outputs by eliminating all unnecessary or useless conditions.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913, By A. I. E. E.

COMPARISON OF METHODS OF LOADING LARGE A-C. AND D-C. GENERATORS AND SYNCHRONOUS CONVERTERS FOR FACTORY TEMPERATURE TESTS

BY F. D. NEWBURY

Object

It is obviously impossible to test the larger machines under energy load at the factory. The advisability of making adequate tests before shipment, to eliminate as completely as possible the greater expense and delay of possible constructional changes after shipment, is generally recognized by consulting engineers and manufacturers. These facts make the question of compromise temperature tests well worth the consideration of the Insitute in connection with the work of the Standards Committee. The author believes the Standards Committee should recommend methods of loading for such factory temperature tests for the guidance of consulting engineers and others responsible for the acceptance of machines, and for the protection of manufacturers against unreasonable demands in connection with such tests. This paper has been prepared with the object of bringing before the Institute data on the relative merits of the various methods of loading which have been suggested and found practicable, and of making recommendations for its consideration.

Requirements of a Satisfactory Test

Any adequate test should duplicate as completely as is possible the conditions under which the machine is guaranteed to operate. In addition to this obvious requirement, the factory test should be *more severe* and not *less severe* than actual operating condi-

tions, and the test conditions of current, voltage, etc., should correspond closely with actual load conditions, so that the comparison between the two can be made directly and without the aid of experimental data.

Description of Methods of Loading A-C. Generators

The following methods of loading have been used more or less extensively and will be considered in this paper:

a. Separate open-circuit and short-circuit tests.
b. Alternate open-circuit and short-circuit tests.
c. Direct-current open-delta test.
d. Zero power factor test.

a. *Separate Open-Circuit and Short-Circuit Tests.* The generator is first tested with the armature winding on open circuit and the field winding excited to give a higher armature voltage and core loss than normal in order to compensate for the absence of the armature winding loss. Then a second test is made during which the armature winding is short-circuited through ammeters and the field excited sufficiently to circulate more than normal full load current. In the open-circuit test, the armature core is the only part subjected to conditions comparable to actual load. The field winding is subjected to less than the maximum operating field current, but the temperature rise is approximately proportional to the loss, so that the temperature rise and exciting voltage can be corrected to maximum load conditions. The temperature rise of the armature winding, being on open circuit, is no guide whatever to the temperature rise under load. In the short-circuit test, the armature winding is the only part subjected to conditions comparable to actual load. The field-winding loss and core loss are altogether too small to give rise to temperatures that would be any guide to actual load temperatures. The open-circuit test, therefore, is of value in predicting armature core and field winding temperature rises and the short-circuit test is of value in predicting armature winding temperature rises.

The open-circuit and the short-circuit tests have the advantage of simplicity in manipulation and in test equipment. No equipment, other than a relatively small driving motor and measuring instruments, is required. For this reason, it is sometimes the only possible method that can be carried out under factory conditions.

The important disadvantage of this method is the difficulty

of properly interpreting the results. This difficulty arises from the fact that the core loss and armature winding loss are not present in the same test, so that the combined effect of the two losses on the core and winding temperatures must be approximated from the separate test results. Experience has shown that in the large majority of machines the normal load core temperature will be lower than the open-circuit core temperature when the open-circuit voltage is approximately 10 per cent higher than normal, and that the normal load armature winding temperature will be lower than the short-circuit test results when the short-circuit current is approximately 25 per cent higher than normal.

These figures can be considered only as rough approximations. It is obvious that the combined effect of the core and copper losses on the temperature of either depends on the relative amount of the two losses, the amount and kind of insulation and the relative temperatures of the core and copper. In high-speed generators, such as steam turbine-driven generators where the core loss is normally three to four times the armature copper loss, the relation between the temperatures resulting from open-circuit short-circuit tests and actual operation will be very different from that in low-speed generators where the core loss is often less than the armature copper loss. In the former class of generators, the core temperature can be predicted with reasonable accuracy from an open-circuit test alone, since the smaller copper loss will have little additional effect, but in the latter case the results from both open-circuit and short-circuit tests must be given serious consideration. The insulation affects the interchange of heat between the core and coils, and for this reason the insulation must be given consideration. Usually, high-voltage machines with their greater thickness of insulation will interchange heat less readily, and a smaller increase in current than 25 per cent for the short-circuit test will give approximately the same results as actual load. The interchange of heat between coils and core will vary in direction, depending on which part has the higher temperature. At normal load, for which the coil temperature will not infrequently be lower than the core temperature, heat will flow from the core to the coils. At overloads, for which the coil temperature will generally be the higher, the flow of heat will be in the opposite direction. In machines such as turbo-generators, in which the problem of ventilation is mainly centered in the core, the flow of heat for all loads may be from the core to the coils.

While these various conditions complicate the interpretation of short-circuit and open-circuit test results, they are subject to simple laws, and the existence of these conditions is not a serious objection to this method of loading, but the results from short-circuit and open-circuit tests are very considerably affected by the efficacy of the ventilation provided in the machine under test, and the correction necessary for this condition cannot be easily nor infallibly applied. In general, in machines in which the core loss is larger than the copper loss the temperature of the core should be relatively low at the end of the short-circuit test. If contrary results are obtained, there is usually some fault in

TABLE I

OPEN-CIRCUIT, SHORT-CIRCUIT AND ACTUAL LOAD TESTS ON 3000-KV-A. 2200-VOLT, THREE-PHASE, 60-CYCLE, 225-REV. PER MIN. WATER WHEEL GENERATORS—DEFECTIVE CORE VENTILATION

	Open circuit	Short circuit	Actual load	Actual load
Length of test in hours	7	8.5	20	12
Volts	2510	0	2280	2520
Amperes per phase	0	985	780	760
Per cent power factor	—	—	98.	90.7
Field amperes	161	65.5	157	178
Field volts on rings	164	57.2		
Temperature rises:				
Stator core	32.5	30	51	53.7
Stator coils	10.5	30	27	20.7
Rotor coils	34.5	12.5	35	46.7
Air temperature	20.5	18	26	39.8

Field coil resistance at 25 deg. cent. = 0.818 ohms.
Armature coil resistance per phase at 25 deg. cent. = 0.016 ohms.
Core loss at 2200 volts = 48 kw.
Core loss at 2510 volts = 63 kw.

the ventilation of the armature core, but this is by no means a complete test for proper ventilation, and the dependence of the proper interpretation of the test results upon ventilation constitutes a serious disadvantage of this method of loading.

In Tables I and II, results from short-circuit and open-circuit temperature tests and tests under actual energy load are given, which illustrate the discrepancies which may occur due to defective ventilation. In these 3000-kv-a. generators, it will be noted that the temperature rise in the core on open circuit was 32.5 deg., and the short-circuit test showed a temperature rise of 30 deg. in both armature winding and core. The tests under normal load showed a temperature rise considerably above the open-

circuit core temperature and an armature coil temperature somewhat below the short-circuit temperature rise. The excessive core temperature was found on investigation to be due to insufficient armature core ventilation, and the results after this defect was corrected (Table II) showed substantial agreement between the results of the open-circuit short-circuit tests and actual energy load. The discrepancy between the core temperatures in the compromise test and in the actual load tests can be explained only on the assumption that on open circuit the low temperature of the armature winding caused a large part of the heat generated in the core to be conducted from the core to the external air through the armature coils, thereby maintaining the core at a fairly low

TABLE II

OPEN-CIRCUIT, SHORT-CIRCUIT AND ACTUAL LOAD TESTS ON SAME GENERATOR AS IN TABLE I AFTER VENTILATION WAS CORRECTED

	Open circuit	Short circuit	Actual load	D-c. open delta	
Length of test hours	7.5	10.5	10	8.5	11
Volts	2320	0	2460	2200	2540
Amperes per phase	0	788	795	788	988
Per cent power factor	—	—	88.5	—	—
Field amperes	159	51.5	181	137	161
Field volts on rings	147.5	44	162	127.5	152
Temperature rises:					
Stator core	27	15.5	33.6	26.8	37.8
Stator coils	16	15.5	17.1	14.8	20.8
Rotor coils	28.5	6.5	33.1	19.3	25.8
Air temperatures	18	20	33	17.2	17.2

temperature. During the load tests, the temperature of the copper in the slots was probably not materially different from that of the core, so that this avenue of escape for the core heat was shut off, resulting in high core temperature.

The difference in actual temperature conditions on open circuit and under a compromise load which experience has shown to approximate actual load, is shown in Table III. These results were obtained by indications from thermocouples located in the center of the slots of a 3800-kv-a., 4000-volt, 60-cycle, three-phase 400 rev. per min. generator. These results show the great influence of the core losses on the coil temperatures, or, in other words, the important part the coils play in conducting heat from the interior of the core to the outer cooling air, particularly

when the loss generated within the coils is negligible. The true conditions are entirely masked by the usual thermometer readings.

A minor disadvantage of the short-circuit and open-circuit method of test is the inability to test the field winding adequately for temperature and exciting voltage margin. The field current used in the open-circuit test is approximately equal to the full-load 100 per cent power factor field current. To test with a field current even approaching that required for the maximum load and low power factor for which the generator is usually designed would result in a prohibitive core loss and temperature. With this method of testing, the guarantees involving the field winding must be checked by calculation from the relatively low

TABLE III

OPEN-CIRCUIT AND ZERO POWER FACTOR TESTS WITH THERMOCOUPLE READINGS OF TEMPERATURE

	Open circuit 4000 volts 0 amperes	0 Per cent power factor 4000 volts 550 amp.	Open circuit 4800 volts 0 amperes	0 Per cent power factor 4800 volts 550 amp.
Core—tooth 1/2 in. below air gap	36	45	55.5	66
Core—1/2 in. below slot	35	44	53.5	62
Core—1/2 in. inside outer surface of core	32	38	48.5	55
Core—outer surface (by thermometer)	23	31	44	47
Max. armature coil temperature in center of core	28.5	40	45	60
Max. armature coil temperature on ends of coils, by thermometer	7	17	18	26.5

field current used in the test. This disadvantage applies not only to the field coil temperature but to the exciting voltage. It is of considerable advantage in a compromise test that the field excitation required should be a maximum. In that event, the exciting voltage shown by the test record will directly indicate the adequacy or inadequacy of the design in this respect.

b. *Alternate Open-Circuit and Short-Circuit Tests.* As has been pointed out, the difficulty in properly interpreting the results from the separate short-circuit and open-circuit tests would be eliminated if both core and copper losses were present in the same test, as in actual operation. To approximate more closely this condition, it has been suggested to test the generator under a succession of short cycles, each cycle consisting of a short-circuit

and open-circuit test. The values of current and voltage during the short-circuit and open-circuit parts of the cycle are determined so that the average core loss during the cycle and the average copper loss during the cycle are equal respectively to the core loss and copper loss during actual load conditions. The average loss during the complete cycle and the loss during normal operation will be equal, and if the length of the cycle is sufficiently short the temperatures should be the same under the test conditions and actual load. The division of time between the open-circuit and short-circuit parts of the cycle may be arbitrarily made within fairly wide limits. If the lengths of time are very different, either core loss or copper loss will have to be abnormally increased to maintain the desired average, so it will be found desirable to divide the cycle into approximately equal parts. If the two losses are sufficiently near together in value, it is of advantage, theoretically at least, to divide the cycle between the two conditions in the ratio of each loss to the total losses. With the time so divided, not only will the average losses during a complete cycle equal the normal load losses during a nequal time, but the core loss during the open-circuit and the copper loss during the short-circuit part of the cycle will equal the sum of the core loss and copper loss during normal operation.

Since this test has only recently been suggested and is probably not as familiar as the other tests discussed, an example will be described in detail. The test described was made on a 6250-kv-a., 6600-volt, three-phase, 60-cycle, 240-rev. per min. waterwheel generator. The core and copper losses under actual load were approximated from separate loss measurements by taking the core loss from the open-circuit core-loss curve at the total induced voltage under normal load and normal voltage and the armature copper loss was taken for normal current from the short-circuit loss curve. This latter loss is greater than that actually existing under load since it includes not only the copper loss but the core loss, and to this extent is an unfavorable assumption. The corresponding favorable assumption would be the use of I^2R loss only. The numerical values for this generator are as follows:

Losses as determined from separate loss test.

At 6640 volts (total induced) core loss =	93 kw.
At 547 amperes short-circuit kw. loss =	72 kw.
Total losses at normal load,	165 kw.

165 kw. open-circuit core-loss is obtained at 8200 volts and 280 field amperes.

165 kw. short-circuit loss is obtained at 875 armature amperes and 125 field amperes.

Dividing the time proportionally to the losses:

$$\text{Time on core loss} = \frac{93}{165} = 56 \text{ per cent.}$$

$$\text{Time on copper loss} = \frac{72}{165} = 44 \text{ per cent.}$$

Choosing a 30-minute cycle, the time on open circuit would be 17 minutes and the time on short circuit would be 13 minutes.

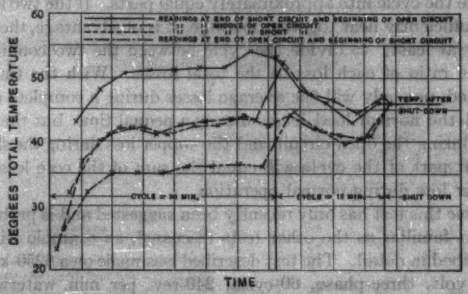


FIG. 1—ALTERNATE OPEN-CIRCUIT AND SHORT-CIRCUIT LOADING—TYPICAL ARMATURE COPPER TEMPERATURES

The value of the field copper loss in kw-hours will be dependent upon the values of open-circuit voltage and short-circuit current assumed. This loss must be compared with the loss under operating conditions and the results interpreted accordingly. In this example, the figures are:

$$\text{Field loss per hour} = 280^2 \times 0.6 \times 0.56 = 26.5$$
$$125^2 \times 0.6 \times 0.44 = 4.15$$
$$30.65$$

The field loss per hour under normal load, 100 per cent power factor, is 19 kw., and at normal load, zero power factor, is 46.5 kw. Thermometer readings were made at the middle and end of each part of the cycle in order to follow the temperature changes. On

a generator of this size, it is not desirable to change from open circuit to short circuit with the full excitation used in the test. The field current was, therefore, reduced to practically zero and brought up again to the short-circuit value in changing from the open-circuit to the short-circuit condition. Typical core and copper temperature logs are shown in the curves, Figs. 1 and 2, and the final temperature results are shown in Table IV.

It will be noted from these results that while the armature and field copper temperatures check fairly well with the results from other methods of loading, the core temperature is much too high.

Results from a similar test on a 150-kv-a., 2400-volt., 60-cycle, 900-rev. per min. belted generator, tested under conditions to

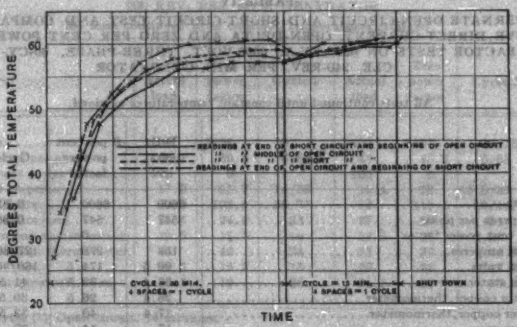


FIG. 2—ALTERNATE OPEN-CIRCUIT AND SHORT-CIRCUIT LOADING—TYPICAL ARMATURE CORE TEMPERATURES

correspond to its normal rating of 150 kv-a., and also under conditions corresponding to 200 kv-a., are shown in Table V.

It will be noted that the results from these cycle tests correspond fairly well with actual load and with zero power factor tests, except in the field copper temperatures.

The temperature logs, Figs. 1 and 2, show:

1. The variation in temperature is much greater in the armature copper than in the armature core, due to the smaller volume of the former and the consequent greater concentration of loss.

2. The longer the cycle the greater this variation. A fifteen-minute cycle appears to be a sufficiently short cycle for a large generator such as the one described.

The high core temperature obtained, in comparison with the core temperatures obtained by other methods of loading, indicates that the losses on open circuit should be reduced possibly to the value found by experience to be correct for the separate open-circuit test. This is the core loss for 110 per cent normal voltage, instead of 124 per cent normal voltage as used in the alternate open-circuit, short-circuit test described. But any such departure from a logical and simple basis to an empirical basis is a decided disadvantage in a standard method of test. While the correct core loss for the test of this generator could be found by comparative tests, the relation so found might or might not apply to another generator of different proportions, depending on all of the

TABLE IV

ALTERNATE OPEN-CIRCUIT AND SHORT-CIRCUIT TEST AND COMPARATIVE DIRECT-CURRENT, OPEN-DELTA AND ZERO PER CENT POWER FACTOR TESTS ON 6250-KV-A., 6600-VOLT, THREE-PHASE, 60-CYCLE, 240-REV. PER MIN. GENERATOR

All tests continued until constant temperatures attained.

	D-C. delta	0 per cent power factor	Cycle
Volts	6600	6600	0/8200
Amperes per phase	547	547	0/867
Per cent power factor		0	
Field amperes	159	278	127/305
Field volts	90.5	174.5	160/380
Rise, stator core	33.4	32.5	41.5
Stator copper, thermometer	26.4	26.5	30.5
Rotor copper, thermometer	17.4	40	33.5
Rotor core	17	14	33
Air temp. room	20.6	22.5	19.5

factors influencing the transmission of heat between the core and winding.

c. *Direct-Current Open-Delta Test.* This method of loading is still closer to the conditions existing under normal operation in that the generator is excited to correspond to normal voltage and the armature winding simultaneously carries current corresponding to normal load. The winding, if not already so connected, is connected in delta, in the case of three-phase winding, or in the equivalent closed winding in the case of two-phase windings, and one corner of the closed winding is opened and direct current is introduced and circulated through the complete winding. Since the alternating voltage is balanced at any corner

of the closed winding, no alternating voltage is introduced in the direct-current circuit and a direct voltage equal to the resistance drop to the alternating-current winding is all that is required. The presence of the direct current in the armature winding results in a stationary field with respect to the armature, having a pole for each phase of each pole of the a-c. generator. With chorded armature windings, the value of this field is reduced, until, with a three-phase winding having a throw equal to two-thirds of the pitch, this direct-current field disappears. These statements can be easily checked by plotting the field form due to

TABLE V

COMPARATIVE TESTS ON 150-KV-A., 2400-VOLT, THREE-PHASE, 60-CYCLE, 900 REV. PER MIN. GENERATOR

All tests continued until constant temperatures attained.

	Actual load	Zero power factor	Cycle 1	Actual load	Zero power factor	Cycle 2
Volts	2400	2400	0/	2400	2400	0/3150
Amperes per phase	36.1	39.5	0/60.3	48	48.2	0/63
Per cent power factor	100	0		100	0	
Field amperes	17.3	25.7	14/53	19.4	28	15.8/31
Field volts	62.5	102.8	20/77	72	119.5	63/127
Rise stator core	24.5	24.5	23	27	30.5	31
Stator cop. thermometer	19.5	15.5	16	23.5	28	21
Rotor cop. thermometer	23	45	24	26	64	49.5
Rotor core	13.5	15.5	13	20	25	17.5
Air temperature, room	23.5	19	25	24.5	20	24.5

Cycle (1) Open circuit, 14 minutes.
Short circuit, 6 minutes.
Cycle during last hour of test reduced to 5 minutes.

Cycle (2) Open circuit, 16 minutes.
Short circuit, 14 minutes.
Cycle during last hour of test reduced to 15 minutes.

the distributed armature winding in the same manner as the field form of induction motors is commonly plotted. Since this direct-current field is stationary with respect to the armature, it generates voltages in any solid part of the field magnets, and since it has three times the number of poles of the generator, the losses due to the stationary field may be considerable if there is any considerable volume of solid metal in the field. In a 3000-kv-a., 225-rev. per. min. 60-cycle generator having laminated poles and solid end plates and with non-magnetic wedges between poles to retain the field coils, this additional loss in the rotating field

magnets amounted to 7.6 kw. In a larger generator of similar construction, this loss amounted to 17 kw. Losses of this magnitude may easily increase the temperature rise of the field coils and so vitiate the test results. This method of test is, therefore, limited to generators in which the magnet poles are mainly laminated, unless the armature winding is considerably chorded. In any event, the additional power required to drive the generator under test should be observed, with and without the circulating direct current, in order to check the additional losses due to it, before reliance is placed upon test results.

The correct field current to use with this method of loading is very little more than the field current to give normal voltage on open circuit, and no appreciable error is introduced by the use of open-circuit normal voltage field current. Obviously, the,

TABLE VI

COMPARATIVE TEMPERATURE RISES—LEADING AND LAGGING 60 PER CENT POWER FACTOR TESTS

	Lagging	Leading
Length of test in hours	11.5	11.5
Volts	6300	6300
Amperes per phase	344	344
Per cent power factor	60	60
Field amperes	135	48
Field volts on rings	102.5	35
Rise, stator core	27.5	27
Stator copper, thermometer	14.5	14
Rotor copper thermometer	14	5.5
Air temperature, room	21	21.5

excitation should be such as to duplicate full-load core loss as nearly as this can be duplicated without alternating current in the armature winding. This condition will be attained when the excitation is sufficient to produce the flux required for the induced voltage with normal terminal voltage and normal armature current. This flux is equal to the flux required to produce an open-circuit voltage equal to the vector sum of terminal voltage, the voltage drop due to armature resistance and the voltage drop due to self-induction of that part of the armature winding *outside of the core*. The larger field current actually required by load conditions (accounted for mainly by armature demagnetization) is neutralized by the armature load current and does not result in increased armature flux. That this value of field current is substantially correct is shown by numerous cases where the results of this method of loading have been compared with

the results from zero power factor method and from actual energy load.

A further check on this same point is afforded by the comparison of test results made at zero power factor or at higher power factors leading and lagging. Such comparative results are shown in Tables VI and VII for a 2250-kw., 3750-kv-a., 6300-volt, three-phase, 50-cycle, 300-rev. per min., synchronous motor operating at 60 per cent power factor leading and lagging and a 6000-kv-a. generator operating at zero power factor leading and lagging.

It will be noted that in both cases the core temperatures are practically the same at the leading and lagging power factors, which indicates very little difference between actual load flux corresponding to the true induced voltage. The reason armature

TABLE VII

COMPARATIVE LEADING AND LAGGING ZERO POWER FACTOR TESTS 6000-KV-A., 400 REV. PER MIN. GENERATOR

Generator operated at normal load until constant temperatures attained, followed by 25 per cent overload for three hours

	Lagging	Leading
Volts	4000	4000
Amperes per phase	1083	1083
Per cent power factor	0	0
Field amperes	177	2
Field volts on rings	222	—
Rise, stator core	40.5	40.5
Stator copper, thermometer	41	37
Rotor copper, thermometer	28.5	6
Air temperature room	24.5	22

self-induction due to that part of the winding in the slots is not included is that this part of the self-induction, like the armature reaction, does not result in an increased flux and generated voltage but merely produces a flux which must be neutralized by the main flux. A further reason why differences in loading do not produce differences in temperature rise, as commonly measured, is that the differences in loss produced by loading occur mainly in the armature teeth where accurate thermometer temperature measurements cannot be made.

Special armature windings having only one coil per slot may introduce irregular direct-current wave forms which will have an effect on the field-core heating and temperature. Whether this is a serious matter can always be determined by plotting the field form or checking the losses due to the direct current.

To summarize, the test conditions of this method of loading

are the same as those existing under actual load, except for the lower field winding loss and for whatever difference results from the use of direct current in the armature winding instead of alternating current. In general, the core temperatures will correspond very closely with those obtained from actual operation. The armature copper temperature will be slightly less than that obtained from actual operation and the field coil temperature and exciting voltage will be considerably less than that obtained from actual operation. The differences in field coil temperature and excitation are not a serious objection to the method of test, since both can be corrected to any desired condition of operation by proportional calculation.

d. *Zero Power Factor Method of Loading.* With this method of loading, the generator under test is operated in parallel with a generator of the same voltage and frequency and of, at least,

TABLE VIII

COMPARATIVE TESTS ON 12,500-KV-A., 6600-VOLT, THREE-PHASE, 50-CYCLE, 300 REV. PER MIN. VERTICAL SHAFT GENERATOR

	Zero power factor	D-C. delta
Volts	6600	6700
Amperes	877	877
Per cent power factor	0	—
Field amperes	281	170
Rise, stator core	35.5	36
Stator copper, thermometer	35	29.5
Rotor copper, thermometer	37.5	17

equal current capacity. The generator under test is over-excited and the generator in parallel with it under-excited until the desired armature current flows. The generator under test, therefore, is operating under normal voltage, normal current and a field current equal to or greater than the maximum value ever required under operating conditions. The test is, therefore, made under more severe conditions than actual full load at any operating power factor.

The one limitation in the application of this method of loading is the necessity for testing equipment equal in kilovolt-ampere capacity to the generator under test. When there are two duplicate generators being built, this limitation obviously does not apply, since one generator can be tested in parallel with the other. This duplicate generator will not always be available and in some cases, and even when it is, the expense for a duplicate test rig

may be prohibitive. This is generally the case with large vertical generators where the thrust bearing is supplied as part of the waterwheel. A large number of comparative tests made at zero power factor and under actual load conditions shows the substantial agreement between the zero power factor and actual loading.

Various tests, from which comparisons between actual load, the direct-current circulating method of loading and the zero

TABLE IX

COMPARATIVE TESTS ON 5000-KV-A., 6600-VOLT, THREE-PHASE, 50-CYCLE, 300 REV. PER MIN. GENERATORS

	Actual load	D-C. delta	Actual load	D-C. delta
Volts	6000	6000	5910	6000
Amperes per phase	480	480	600	600
Per cent power factor	100		100	
Field amperes	128.5	118	136	118
Field volts on rings	145	125	155	125
Rise, stator core	34	35	43	42
Stator copper, thermometer	30	25	46	40
Rotor copper, thermometer	26	25.5	27	29

TABLE X

COMPARATIVE TESTS ON 1400-KV-A., 2300-VOLT, THREE-PHASE, 60-CYCLE, 200 REV. PER MIN. GENERATORS

	Open circuit	Short circuit	D-C. delta	0 per cent power factor
Volts	2550	0	2300	2300
Amperes per phase	0	440	352	352
Per cent power factor				0
Field amperes	106.5	53	97	139
Rise, stator core	20.5	10	22	24.5
Stator copper, thermometer	9	7	14.5	17
Rotor copper, thermometer	10	3	8	16.5

power factor method of loading can be made, are given in Tables VIII, IX and X. Comparative results from d-c. open delta and actual load tests are also given in Table II. From Table VIII, it will be noted that in the direct-current circulating test the field excitation was slightly above that required for open-circuit normal voltage and the core temperature was slightly above that obtained on the zero power factor test. This bears out the statement made in connection with the proper value of field current

in the direct-current circulating test. It will also be noted that the armature winding temperature rise is somewhat lower on the direct-current test than on the zero power factor test.

Conclusions

Of the four methods of loading discussed, it is the author's opinion that the zero power factor method more nearly approaches the requirements of a satisfactory method of loading, as outlined in the early part of this paper. The conditions in this method of loading correspond almost exactly with conditions of actual operation, so that no question can arise as to the proper voltage, armature current and field current to use in the test, and whatever differences exist make the test more severe and not less severe than actual load. The tests also gives a direct indication of the field coil temperature and exciting voltage under maximum conditions of operation. If, on account of lack of equipment, this method of loading is not feasible, the author recommends that the direct-current circulating test and the separate short-circuit and open-circuit method be substituted, in the order given. The alternate short-circuit and open-circuit test is not recommended, on account of the wide divergence from actual operating conditions, making the question of correspondence between the conditions of test and conditions of operation entirely one of judgment and experience in which the two parties concerned may not agree. However, as experience with this method of loading is accumulated, it may prove preferable to the separate open-circuit and short-circuit method, as it does more nearly approach actual operating conditions than the separate tests.

Methods of Loading Large D-C. Generators and Synchronous Converters

There has been only one method of loading suggested or used which gives results of any value in comparison with the results from actual operation. This method is the well-known "loading back" method in which two machines of equal capacity are operated together, one as a generator and the other as a motor. The correspondence with actual operating conditions is exact as far as commutation and temperature on steady load are concerned. Where a second machine is not available, the field coil temperature can be checked by an open-circuit test. The core and copper temperatures on such a test are of very little value on account of

the absence of the relatively large armature copper loss. The commutation, however, can be checked by operating at zero voltage or reduced voltage and normal current, in case the generator is provided with commutating poles. Such tests are advisable but do not afford any adequate test of temperatures.

It is recommended that, the loading-back method of test be used for d-c. generators and synchronous converters when the necessary apparatus is available at the factory and the generator is too large to test on a resistance load.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

COMPARISON OF METHODS OF MAKING LOAD TESTS ON A-C. GENERATORS AND ON INDUCTION MOTORS

BY E. F. COLLINS AND W. E. HOLCOMBE

The object of this paper is to outline briefly some of the most practical methods that have been employed for obtaining the normal running temperatures of alternators and induction motors under no-load or partial load conditions.

Nearly all the methods treated have been discussed in scientific papers at home and abroad and are known to most electrical engineers. It is our intention to speak of these methods only in a general way and to submit data showing comparative results obtained in regular commercial testing.

The chief reasons for testing by these no-load methods are in order that the cost of testing may be materially reduced, and because machines are being built in such numbers and of such capacity that the manufacturer cannot economically provide power supply and testing equipment for the actual loading of all machines.

I. Alternators

The methods for making heat runs on alternators, with which this paper deals, will be designated as follows:

1. Zero power factor method.
   a. Leading current.
   b. Intermittent leading and lagging current.
2. Open- and short-circuit method.
   a. Continuous run.
   b. Intermittent run.
3. Open delta method.
4. Phase displacement method.

1. Zero Power Factor Method

a. *Leading Current.* The machine to be tested is operated as a synchronous motor running free at normal voltage and normal leading current in the armature, obtained by over-exciting the field. As practically the whole armature reaction directly opposes the field, the field current is greater than under any other condition of normal armature voltage and current. The normal field heating can, however, be approximated by reducing the observed temperature rise in proportion to the respective field losses.

This method has given very good results and has been extensively used in testing turbo-alternators. The main error of the method is that the field heating will be greater than occurs when operating under full load.

b. *Intermittent Leading and Lagging Current.* The above method is modified by operating the machine alternately for short periods with leading and lagging currents in the armature. The two periods may be adjusted so that the average loss is equal to normal.

Let I_0 be the field current required for over-excitation, I_u the current required for under-excitation, I_n the normal field and X the per cent of a complete cycle (consisting of a period of over-excitation and a period of under-excitation) during which over-excitation is used, then

$$I_0^2 X + (1 - X) I_u^2 = I_n^2$$

or

$$X = \frac{I_n^2 - I_u^2}{I_0^2 - I_u^2}$$

In this method an attempt is made to compensate for the excessive field heating of the previous case by running the machine intermittently over-excited and under-excited, the time interval to be such as to give normal heating in the field. This method has been found to give excellent results.

The only practical objection to the zero power factor method is that it requires equivalent kv-a. supply, which is not always available.

Tables IA, IB and IC give data comparing results obtained from zero power factor tests with those from actual load on same machine.

TABLE I A

THREE-PHASE, 60 CYCLES, 2500 KV-A., 1800 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Zero power factor, leading
Armature laminations	35	35
" ducts	31	29
" coils	29	23
" " (res.)	34	27
Field coils (res.)	41	68
" " " reduced to normal	—	42

TABLE I B

*THREE-PHASE, 60 CYCLES, 715 KV-A., 720 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Zero power factor leading	Zero power factor Leading 7 min. Lagging 13 min.
Armature laminations	30	36	29
" ducts	23	36	28
" coils	30	35	26
" " (res.)	28	44	30
Field coils	26	54	37
" " reduced to normal	—	19	—
" " (res.)	38	60	38
" " " reduced to normal	—	24	—

TABLE I C

* THREE-PHASE, 60 CYCLES, 257 KV-A., 720 REV. PER MIN., 2530 VOLTS

Maximum temperature rise	Full load	Zero power factor leading	Zero power factor, Leading 3.5 min. Lagging 5.5 min.
Armature laminations	22	22	19
" ducts	20	23	18
" coils	16	20	15
" " (res.)	31	18	23
Field coils	32	77	32
" " reduced to normal	—	36	—
" " (res.)	42	102	44
" " " reduced to normal	—	48	—

* Location of thermometers was the same for these runs

2. Open- and Short-Circuit Method

a. *Continuous Run.* This method consists in running the machine a certain percentage above normal voltage on open circuit until temperatures are constant, then a certain percentage above normal current on short circuit until temperatures are constant. A maximum-rated generator is usually operated at

110 per cent normal volts and 110 per cent normal current, while higher percentages are used with generators that are designed to carry overloads. The core loss when operating above normal voltage is assumed to heat the armature core to approximately the same temperature as it would be heated when operating under normal voltage and current. The I^2R in the armature coils when running above normal current is assumed to heat the coils to approximately the same temperature as when operating at normal voltage and current.

On open circuit the voltage taken is assumed to be that which would correspond to a core loss equal to the combined armature losses under load. Hence, in the successful application of this method an approximate knowledge of the core loss curve and total armature losses under load is necessary.

Likewise, the short-circuit current is taken a certain percentage above normal. In some cases this current may cause a heating in the coils which is in excess of the heating on full load. On the other hand, on all classes of machines and particularly on machines using forced ventilation, the amount of the cooling air is proportional to the total losses in the machine. With the absence, therefore, of the core loss in armature, which may form a considerable part of the total losses, the heat conduction to a relatively cool core may be more rapid than would be the case were the machine loaded.

Tables IIA, IIB, IIC and IID give data comparing results obtained from the open- and short-circuit method (continuous) with those from actual load on the same machines.

b. *Intermittent Run.* The generator to be tested is run alternately open and short-circuited. The length of time for a complete cycle usually varies from four to fifteen minutes.

Let X be the per cent of the time during which the machine is short-circuited, I_c the normal armature current and W_c the normal core loss. When the machine is operated open-circuited, the field current is adjusted to give a voltage such that the core loss is equal to $\frac{W_c}{1-X}$, and when operated short-circuited, so that the armature current is $\frac{I_c}{\sqrt{X}}$. If I_0 and I_s are the field currents for the periods of open circuit and short circuit respectively, and I_n the normal field current, the average field current will be

$$\sqrt{I_s^2 X + I_0^2 (1-X)}$$

TABLE II A

*THREE-PHASE, 60 CYCLES, 2500 KV-A., 1800 REV. PER MIN., 2300 VOLTS

Maximum temperature rise, deg. cent	*Full load	Open-circuit 110 per cent volts	Short-circuit 120 per cent amperes
Armature laminations	35	36	—
" ducts	31	28	—
" coils (thermo.)	29	—	35
" " (res.)	34	—	45
Field winding	41	48	—

* Average of runs on two similar machines.

TABLE II B

THREE-PHASE, 33 CYCLES, 5400 KV-A., 1990 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Open-circuit 110 per cent volts	Short-circuit 122 per cent amperes
Armature laminations	25	20	—
" ducts	24	16	—
" coils	22	—	34
Field winding (res.)	38	25	—

TABLE II C

†THREE-PHASE, 60 CYCLES, 715 KV-A., 720 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Open-circuit 110 per cent volts	Short-circuit 110 per cent amperes
Armature laminations	30	25	—
" ducts	23	24	—
" coils	30	—	30
" " (res.)	28	—	32
Field coils	26	21	—
" " (res.)	38	35	—

† Thermometers were in the same location for all runs.

TABLE II D

THREE-PHASE, 60 CYCLES, 3000 KV-A., 514 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Open-circuit 110 per cent volts	Short-circuit 125 per cent amperes
Armature laminations	32	30	—
" ducts	29	24	—
" coils	25	—	24
" " (res.)	34	—	30
Field coils	21	29	—
" " "	21	29	—

the value of X being so chosen that the average field current will be equal to I_n. If this is done, the average losses due to armature current, core loss and field excitation should be about the same as under load. It is not always possible to choose a value for X that will make the average field loss equal to the normal field loss, but the field heating can be approximated.

In some generators the short-circuit core loss is considerable and cannot be neglected. This can be taken care of by slightly modifying the intermittent method.

If W_s be the short-circuit core loss corresponding to armature current $\frac{I_a}{\sqrt{X}}$, used during period of short-circuit, the total loss supplied during interval X will be $W_s X$. This loss should be subtracted from the normal core loss to find the core loss to be supplied during the period of open circuit. This loss will be

$$\frac{W c - W s X}{1 - X} \text{ instead of } \frac{W c}{1 - X}$$

Several tests have been made by this method and the temperatures obtained agree fairly well with load temperatures. In the practical application of this method judgment should be exercised in selecting periods obtained by the foregoing formula so that the armature winding may be not subjected to excessive currents that result in damage to insulation before a dangerous temperature is recorded on a thermometer applied to the external surface.

This test requires a knowledge of both the open- and short-circuit core loss before the run is begun, which sometimes handicaps its use.

Tables IIE, IIF and IIG give data comparing results obtained from the intermittent open- and short-circuit method with those from actual load on the same machines.

3. Open Delta Method

The armature winding of a three-phase machine is connected in delta with one corner open and direct current is introduced at this point. The fields are excited with that current which gives normal volts when the machine is operating under full load. The excitation is calculated from the saturation and impedance curves.

In many machines an alternating cross current may flow in the delta, due to the harmonics. When this current exists it is meas-

ured and combined vectorially with the applied direct-current value. The proper value of the current to give armature copper loss corresponding to normal load current (I_a) will be equal to

TABLE II E

THREE-PHASE, 60 CYCLES, 2500 KV-A., 1800 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Intermittent run Open-circuit 10 min. 117 per cent volts short-circuit 5 " 173 per cent amperes
Armature laminations	36	32
" ducts	31	29
" coils	29	17
" " (res.)	34	22
Field " "	41	37

TABLE II F

*THREE-PHASE, 60 CYCLES, 715 KV-A., 720 REV. PER MIN., 2300 VOLTS

Maximum temperature rise	Full load	Intermittent run 7.5 min. open-circuit 116 per cent volts. 7.5 " short-circuit 143 per cent amp's.
Armature laminations	30	29
" ducts	23	30
" coils	30	40
" " (res.)	28	40
Field "	26	25
" " (res.)	38	34

* Location of thermometers the same for both tests.

TABLE II G

* THREE-PHASE, 60 CYCLES, 257 KV-A., 720 REV. PER MIN., 2530 VOLTS

Maximum temperature rise	Full load	Intermittent run 4 min. short-circuit 152 per cent amp's. 5.5 " open- " 113 per cent volts
Armature laminations	22	19
" ducts	20	18
" coils	16	15
" " (res.)	31	23
Field "	32	32
" " (res.)	42	44

* Thermometers in same position for both runs.

$I_d = \sqrt{I_a^2 - I_c^2}$ where I_d equals the applied direct current and I_c equals the circulating current due to the harmonics.

This method may be used on other than three-phase alternators by properly splitting and connecting the stator windings so as to

obtain zero or a low potential across the opening into which the direct current is introduced.

Satisfactory results have been obtained in some cases by this method, but it is unreliable for general testing. This is largely due to the fact that the direct current in the armature forms a

TABLE III A
* THREE-PHASE, 60 CYCLES, 715 KV-A., 720 REV. PER MIN., 2300 VOLTS
SALIENT POLE MACHINE

Maximum temperature rise	Full load	Open delta
Armature laminations	30	29
" ducts	23	25
" coils	30	25
" " (res.)	28	26
Field "	26	21
" " (res.)	38	32

* Location of thermometers the same for both runs.

TABLE III B
THREE-PHASE, 60 CYCLES, 2500 KV-A., 1800 REV. PER MIN., 2300 VOLTS
NON-SALIENT POLE MACHINE

Maximum temperature rise	†Full load	Open delta
Armature laminations	35	51
" ducts	31	53
" coils	29	37
" " (res.)	34	45
Field " "	41	108

† Average of two similar machines.

TABLE III C
THREE-PHASE, 60 CYCLES, 300 KV-A., 1800 REV. PER MIN., 480 VOLTS
NON-SALIENT POLE MACHINE

Maximum temperature rise	Full load	Open delta
Armature laminations	25	31
" ducts	22	27
" coils	21	27
" " (res.)	38	33
Field " "	19	41

magnetic pole out of each group of coils per phase, which results in a pulsating flux and abnormal losses.

Tables IIIA, IIIB and IIIC give data comparing results obtained from the open delta method with those from actual load on the same machines.

4. Phase Displacement Method

Duplicate generators are assembled with their fields coupled together in such a way that a displacement of phases may be obtained by shifting one field with respect to the other or by shifting armature frames. A direct-current motor of sufficient capacity to take care of the losses in both machines is used to drive the generators at normal speed. The required condition of load and power factor must be obtained by trial. The stators are connected together electrically for proper phase rotation so that one machine acts as the motor and the other as the generator.

This method will give results in all cases identical with those obtained under actual load.

TABLE IV
THREE-PHASE, 60 CYCLES, 2500 KV-A., 1800 REV. PER MIN., 2300 VOLTS
TEMPERATURE RISES, DEG. CENT.

	1	2	3	4	5	6
Armature laminations	35	35	51	36	—	32
" ducts	31	29	53	28	—	29
" coils (ther.)	29	—	37	—	35	17
" " (res.)	34	27	45	—	45	22
Field winding (res.)	41	68	108	48	—	37
" " corrected	—	42	—	—	—	—
Room	24	19	24	30	31	27

Column 1. Average of two runs on similar machines, 100 per cent power factor, actual load.
Column 2. Zero power factor method, over-excited field.
Column 3. Open delta method.
Column 4. Open-circuit run at 110 per cent normal volts.
Column 5. Short-circuit run at 120 per cent normal amperes.
Column 6. Intermittent run: open-circuit 10 min., 117 per cent volts; short-circuit 5 min., 173 per cent amperes; repeated until temperatures were constant.

The principal objection to this method is that it requires two identical machines, and may be used only when it is possible and practical to couple them together.

Tables IV and V show comparative temperatures obtained on the same machine run in accordance with the several methods described.

The temperatures recorded for the 715-kv-a. machine were obtained during successive runs and the thermometers on the machine were not disturbed during the entire progress of the tests. The rotating parts were also marked so that the thermometers were always applied to the same points when machine was shut down.

TABLE V

THREE-PHASE, 60 CYCLES, 715 KV-A., 720 REV. PER MIN., 2300 VOLTS

TEMPERATURE RISES, DEG. CENT.

	1	2	3	4	5	6	7	8	9
Armature core lam. (max.)	30	32	36	29	38	25	29	35	29
" " " (av.)	29	31	34	28	36	23	28	33	28
Armature core ducts (max.)	23	34	36	28	37	24	30	36	25
" " " (av.)	22	29	32	26	35	23	27	31	23
Armature coils (max.)	30	30	35	26	37	30	40	51	25
" " (av.)	25	27	32	23	36	27	34	42	23
Armature coils res. (max.)	28	37	44	30	46	32	40	47	26
" " " (av.)	28	37	44	30	46	32	40	47	—
Field spiders (max.)	18	22	27	17	28	16	18	24	19
" " (av.)	18	21	27	17	27	15	17	23	19
Collector rings (max.)	18	16	30	19	32	23	20	20	12
" " (av.)	17	15	28	18	31	21	20	19	12
Pole tip lead (max.)	23	27	34	19	31	17	20	29	22
" " " (av.)	22	26	33	19	31	17	20	28	22
Pole tip trail (max.)	23	27	33	20	28	16	20	32	22
" " " (av.)	22	26	32	20	27	16	19	29	22
Bridges (max.)	24	28	57	19	31	22	23	36	20
" (av.)	24	27	51	19	29	20	22	32	20
Squirrel cage (max.)	18	20	20	15	25	12	16	26	15
" " (av.)	18	19	20	14	23	12	16	23	15
Spools (max.)	26	45	50	22	31	21	25	42	21
" (av.)	26	35	54	21	30	21	23	39	21
Spools by resistance*	38	50	69	38	59	35	34	59	32
" " " †	22	37	60	24	32	23	25	36	24
Frame (max.)	17	18	19	16	21	14	16	20	16
" (av.)	17	17	19	16	21	13	16	19	15
Room (max.)	20	23	21	19	21/23	25/22	22	21	18
" (av.)	20	23	21	19	—	25	22	22	—

* Resistance by voltmeter and ammeter.

† Resistance by galvanometer.

Column 1. Machine running as a motor, full load, 100 per cent power factor.

Column 2. Full load, 80 per cent power factor, leading.

Column 3. Zero power factor method with field over-excited to give full load current in armature.

Column 4. Zero power factor method, over-excited 7 min. and under-excited 13 min., except during last hour of run, when periods were changed to 3½ min. over-excited and 6½ min. under-excited.

Column 5. Sum of temperatures from open- and short-circuited runs at normal voltage and normal current.

Column 6. Temperatures from open-circuit run at 110 per cent volts for the iron parts and field, and from short-circuit run at 110 per cent current for armature coils.

Column 7. Intermittent run, 7.5 min. open-circuit at 116 per cent volts and 7.5 min. short-circuit 143 per cent amperes.

Column 8. Intermittent run, open- and short-circuited with periods determined from excitation for 80 per cent power factor condition, 5 min. open-circuit at 140 per cent. volts and 10 min. short-circuit at 130 per cent amperes.

Column 9. Open delta method.

Conclusions

We believe the zero power factor method with intermittent leading and lagging current to be the best substitute for full load test, since the losses have approximately the same distribution as exist in the machine under load. This conclusion is confirmed by the results of the foregoing temperature tests. The zero power factor method with leading current gives practically the same values, with the exception of greater heating on the field. This can be readily corrected for normal field loss.

The open- and short-circuit method has been extensively used, and when proper values of voltage and current are chosen, will give results agreeing fairly well with actual load values. It is primarily recommended as a checking test on machines whose temperatures have previously been determined by the zero power factor or actual load methods, and whenever it is not practical or convenient to use these methods.

II. Temperature Tests which Approximate Actual Load Conditions for Induction Motors

The methods described are as follows:

1. Feeding-back method.
2. Reduced voltage method.
3. Reversed rotation method.

1. Feeding-Back Method

This test is made by belting together two induction motors, in such a manner as to make one run above and the other below synchronous speed. The amount that each differs from synchronous speed is the normal slip for that load. The stators are connected in multiple to an a-c. supply of normal frequency and voltage.

One machine acts as a generator and the other as a motor. Temperatures obtained on the motor under these conditions of load will equal normal operating temperatures.

This method involves difficulties in obtaining proper pulley diameter and is limited by the power that is readily transmitted by belting.

Where the induction motor is direct-connected to a d-c. machine and two sets are available, the feeding-back method may be used in all cases and temperatures will be obtained equivalent to those of full load.

2. Reduced Voltage Method

This test is made by running the motor free at normal volts until temperatures are constant. The motor is then operated at a reduced voltage and sufficient load to give the required current. The kv-a. input is usually $\frac{1}{4}$ to $\frac{1}{2}$ of normal and the power output about 1/16 to $\frac{1}{4}$ of normal. Although the load carried at reduced voltage is small, the slip from synchronous speed exceeds that for the same primary current at normal voltage. Full-load speed is desirable and is obtained by raising the frequency of supply a small percentage.

The temperature rise on the stator at full load may be determined from the above method as follows:

T_f = Temperature rise on stator for full-load normal volts.
T_n = Temperature rise on stator for no-load normal volts.
T_r = Temperature rise on stator for reduced voltage run.
E_n = Normal voltage.
E_r = Reduced voltage.

$$T_f = T_r - \frac{T_n E_r^2}{E_n^2} + T_n$$

The same method of calculation may be followed for any load. The rotor temperature is to be taken as observed on reduced voltage run. As a rule, the calculated temperature rises from this method are somewhat greater than those obtained from actual load.

Tables VI, VII, VIII, IX and X give data comparing temperatures from actual load with temperatures obtained by the reduced voltage method.

TABLE VI
THREE-PHASE, 60 CYCLES, 20 H.P., 1200 REV. PER MIN., 220 VOLTS

Maximum temperature rise in deg. cent.	Full load	Normal amperes 80 volts	Running free at normal volts	Corrected for full load	125 per cent load	125 per cent normal amperes 80 volts	Corrected for 125 per cent load
Stator laminations..	25	20	14	32	33	27	39
" ducts	20	17	8	24	28	23	30
" coils.....	20	18	7	23	27	25	30
" " (res.)....	25	—	10	—	30	—	—
Rotor conductors...	18	18	6	18	25	20	20

TABLE VII

* THREE-PHASE, 60 CYCLES, 20 H.P., 1200 REV. PER MIN., 220 VOLTS

Maximum temperature rise	Full load	Normal current 80 volts	Running free at normal volts	Corrected for full load	125 per cent full load	125 per cent current 90 volts	Corrected for 125 per cent load
Stator laminations..	22	19	15	32	29	29	41
" ducts.....	19	16	10	25	29	23	31
" coils.....	16?	21	12	31	27	27	37
" " (res.)...	25	26	16	40	35	33	46
Rotor conductors...	15	* 16	11	16	22	23	23

* Location of thermometers not changed during run.

TABLE VIII

THREE-PHASE, 60 CYCLES, 50 H.P., 900 REV. PER MIN., 440 VOLTS

Maximum temperature rise	Full load	Normal amperes 220 volts	Running free at normal volts	Corrected for full load
Stator laminations.....	24	19	10	26
" ducts.....	16	12	4	15
" coils.....	18	14	5	18
" " (res.).....	32	23	22	39
Rotor conductors.....	17	18	6	18

TABLE IX

* THREE-PHASE, 60 CYCLES, 100 H.P., 720 REV. PER MIN., 550 VOLTS

Maximum temperature rise	Full load	Normal current 156 volts	Running free at normal volts	Corrected for full load	125 per cent full load	125 per cent current 238 volts	Corrected for 125 per cent load
Stator laminations..	24	15	12	26	34	24	34
" ducts.....	20	14	9	22	25	22	32
" coils.....	23	14	7	20	30	25	31
" " (res.)....	29	16	9	24	31	27	35
Rotor conductors...	16	7	5	7	24	18	18

* Location of thermometers not changed during runs.

TABLE X

* THREE-PHASE, 60 CYCLES, 250 H.P., 600 REV. PER MIN., 440 VOLTS

Maximum temperature rise	Full load	Normal amperes 130 volts	Running free at normal volts	Corrected for full load	125 per cent amperes	165 volts	Corrected for 125 per cent load
Stator laminations..	22	21	10	30	33	32	40
" ducts.....	21	17	7	23	30	30	36
" coils.....	21	19	6	24	29	31	36
" " (res.)....	23	18	10	27	33	31	39
Rotor conductors...	20	20	5	20	23	33	33

* Location of thermometers not changed during runs.

3. Reversed Rotation Method

This test is made by driving the rotor at normal full-load speed in a direction opposite to that in which it has a tendency to turn when current is applied to the stator. The impressed volts on stator are adjusted to give the current corresponding to any load.

This method appears to be a practical one and gives temperature rise on the stator in most cases that very closely approaches normal running temperatures. It is difficult, however, to completely explain why the temperatures obtained are in such close agreement with those obtained under actual load.

Tables XI, XII and XIII give data comparing temperatures from actual load with those obtained by this method.

TABLE XI

* THREE-PHASE, 60 CYCLES, 250 H.P., 600 REV. PER MIN., 440 VOLTS

Maximum temperature rise	Full load	Reversed rotation normal amperes	125 per cent load	Reversed rotation 125 per cent amperes
Stator laminations.....	22	19	33	31
" ducts.....	21	17	30	27
" coils.....	21	19	29	34
Rotor conductors.....	20	15	23	22

* Location of thermometers same for all runs.

TABLE XII

* THREE-PHASE, 60 CYCLES, 100 H.P., 720 REV. PER MIN., 550 VOLTS

Maximum temperature rise	Full load	Normal amperes reversed rotation
Stator laminations.....	24	23
" ducts.....	20	20
" coils.....	23	25
" " (res.).....	29	30
Rotor conductors.....	16	18

* Location of thermometers same for all runs.

TABLE XIII

*THREE-PHASE, 60 CYCLES, 20 H.P., 1200 REV. PER MIN., 220 VOLTS

Maximum temperature rise	Full load	Normal amperes reversed rotation	125 per cent load	125 per cent amperes reversed rotation
Stator laminations	25	18	33	26
" ducts	20	18	28	24
" coils	20	17	27	23
" " (res.)	25	18	30	26
Rotor conductors	18	17	25	23

* Location of thermometers same for all runs.

From the data presented it will be noted that both the reduced voltage and reversed rotation methods give temperatures closely approximating those obtained under actual load. The distribution of losses in the machine under the reduced voltage method is more nearly normal than in the reversed rotation method. Either method is easily applied and requires the expenditure of only a small amount of power, compared with the rated output of the motor under test.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

NOTES ON METHODS OF MAKING LOAD TESTS ON LARGE INDUCTION MOTORS

BY A. M. DUDLEY

It is desirable, wherever it is possible, to test apparatus fully in all respects before it leaves the premises of the manufacturer. Where this can be done and the results carefully checked by both parties to the contract there is little possibility of the units failing to do in service what was expected of them.

In the case of induction motors such complete tests include a check on the efficiency, power factor, torques, heating, noise, mechanical balance and temperature. With the exception of temperature, it is possible to make observations with the motor at standstill or running under no load which will indicate closely to the trained observer what may be expected of the machine, with reference to the different characteristics enumerated. It is also true to a degree that these same observations give the losses in the various parts of the motor and in this way are a check on the temperature. This check is more evident to the designer, on account of his experience with the amount of loss that his various frames will dissipate, than it is to the man of less experience who represents the ultimate user and who is endeavoring to satisfy himself that the machine in all respects meets the specifications to which the manufacturer is working. For this reason it is desirable to load up the motor to as nearly exactly its normal operating condition as can be reached and make observations of the temperature rise in the various parts.

In the case of motor-generator sets driven by induction motors which come through manufacture in pairs, it is possible by the simple expedient of circulating the power around through all the machines, to secure full-load temperature tests on four

machines at an expense merely of making up from an outside circuit an amount of power represented by the losses of the four units. It is also possible, in the case of separate units coming through in pairs, to make a full-load run at a reasonable expense. This may be accomplished in at least two ways. The first depends on the mechanical connection between the two units at the time one is running as a motor and the other as a generator. In practise this is worked out by belting the two machines together, with a pulley on the unit which is to act as a motor, slightly larger than the pulley on the unit which is to act as a generator. When the machines are started up and both are connected to the same source of alternating-current supply there is a tendency for one machine to drive the other slightly above synchronism due to the difference in pulley diameters. If this difference has been chosen or can be adjusted so that it is approximately twice the full-load slip of the units when running normally, the result will be that the combination will automatically divide this difference on either side of synchronous speed and one will run fully loaded as a motor below synchronism and the other fully loaded as an asynchronous generator above synchronism. Since the generator returns to the circuit all the power taken by the motor, with the exception of the full-load losses in both machines, this method is economical. It has the disadvantage, practically, that it is difficult to select or adjust the pulley diameters exactly as they should be.

The same result can be accomplished electrically by having available two sources of alternating-current supply, which can be adjusted so that the frequency of one will be slightly higher than the other. The two units undergoing test are then directly connected by some form of positive coupling and the motor unit is connected to the current supply which is to be higher in frequency. The generator unit is then connected to the source of lower frequency, and since it runs at the same rev. per min. as the motor, it is really running above synchronous speed as referred to the circuit to which it is electrically connected. The two sources of external power supply are then adjusted with just the proper difference in frequency to cause both the tested units to run under full-load conditions, one as a motor and one as an asynchronous generator. As the two sources of external power supply are presumably from a common source still further back, it is possible to balance up the consumed and regenerated energy so that only the full-load losses of the two tested

machines need be supplied externally. This method works out very satisfactorily and is frequently employed in making such tests.

Two units are not always available, and in that case, if the machine to be tested is one of large capacity, it may be difficult or impossible to make a full-load test. The reasons for this are obvious. The manufacturer may not have available the necessary mechanical facilities in the way of shafting, bearings, pulleys, belts or gears to line up the motor so it can be loaded, or there may be no suitable machine to serve as a load for the tested motor or to drive the tested motor as a generator, and last, but by no means to be considered negligible, the expense of conducting such a dead load test, from the standpoint of the power consumed alone, would be considerable. For example, a unit of 1000 h.p. would have a full-load input in the neighborhood of 800 kw. and this load for ten hours at one cent per kw-hr. would amount to $80.00.

For these practical reasons it is necessary in such cases to adopt some form of compromise test, which, while it may not give exactly the same results as actual full load, will give a sufficiently close approximation to judge the actual temperatures under operating conditions after installation.

There are a number of different methods of accomplishing this result, of which the following may be mentioned:

1. Operating the unit under test as a motor on normal frequency but at reduced voltage and developing a reduced torque.

2. Driving the tested unit as an a-c. generator by a small auxiliary motor and making compromise tests after the methods followed on a-c. generators. These may consist of over-exciting one member with direct current so as to give high iron losses, or using a lower excitation with the other member short-circuited so as to give high copper losses.

3. Operating the tested unit as a motor without load but at a voltage higher than normal in the effort to increase the iron and no-load copper losses to a sum approximating the full-load copper and iron losses.

4. Operating the tested unit as a motor on a cycle where it will alternately run light for a period at over-voltage and for another period at low voltage and a light load sufficient to cause full load or somewhat greater current to flow in the windings.

5. Connecting the tested unit to a supply circuit at a greatly reduced voltage and driving it against its normal direction of

rotation by a separate motor. By varying the voltage applied it is possible to cause any desired current to flow in the windings, with proportionate heating.

Considering these methods in order, they will be found to give the following results:

1. In this case it is possible to get full-load copper losses but there is necessarily only a small proportion of the full-load iron loss present. The copper losses may be increased to approximate the iron loss, but the losses so created are distributed differently from those in the normally operated and loaded machine and the resulting temperatures are affected thereby. Such tests ordinarily show the copper temperatures higher than normal and the iron temperatures somewhat lower.

2. These tests are similar in every way to the same tests conducted on a-c. generators. As is shown in Table V, in some cases they give results very close to the tested values under actual load.

3. This method resembles method (1) in the fact that the distribution of losses is different from the normal machine. This test usually shows the iron temperatures too high and the copper temperatures too low. There is a practical limit to the amount the voltage may be increased, due to the limits of the insulation.

4. This test, with a proper selection of the proportion of total time for the various parts of the cycle and the frequency of their alternation, can be made to give results very closely approximating full-load conditions. It is hardly safe, however, to adopt a general cycle as applicable to all machines, on account of the varying proportions of copper and iron losses in machines of different characteristics. Data on this method, where available, indicate very satisfactory results.

5. This method has proved very satisfactory in a large number of instances. It is, however, open to criticism in that it imposes on the rotor core a frequency of about twice the normal primary frequency. This does not occasion any material error from the standpoint of iron loss in the rotor core, since the applied primary voltage and the resulting densities are fairly low. It does, however, occasion considerably increased rotor copper losses due to eddy currents caused by the high secondary frequency. As shown in Tables I and V, this is ordinarily of no consequence on 25-cycle machines. Tables II, III and IV show, however, that it may materially increase the rotor temperatures on 60-cycle machines and through these, the temperatures of the whole

machine. One of the advantages of this method is that it is safe, *i.e.*, it shows temperatures on test which are higher, if anything, than they will be under actual load conditions. It may, therefore, be concluded that, if a machine has been operated in this way and the temperatures are within specified limits, the temperatures under normal operating conditions will be within the same limits. Unfortunately, the converse is not equally true, *i.e*, a machine may show under this test temperatures which are higher than the specified limits and which under actual load conditions may be well inside these same limits. But this is a good fault in any compromise method and should not detract from the excellent results which follow generally from its use.

As the writer's experience has been more largely in connection with method (5), he offers in the tables some typical examples of tests conducted in this way. In every case the columns marked "circulating current" are tests taken in this way, *viz*: a current of normal frequency and greatly reduced voltage is applied to the motor terminals and it is driven against the normal direction of rotation at full-load speed. The applied voltage is then varied until the desired current flows in the windings.

TABLE I

INDUCTION MOTOR—PHASE-WOUND ROTOR

Rating: 1000 h.p., 25 cycles, three-phase, 2200 volts, 12 poles, 245 rev. per min.

Losses.

Primary copper	11,600 watts
Secondary copper	13,800 "
Core loss	7,700 "
Bearing friction and windage	6,400 "
Total	39,500 watts

TEMPERATURE DATA

Kind of load	Actual load driving generator			Circulating current
Length of test in hours	8	2	7½	8½
Volts	2247	2220	2240	360
Per cent normal full-load amperes	139	170	150	139
Rise, in deg. cent., stator core	31	40.5	36.5	29
" stator copper (thermometer)	33.5	47.5	39	38
" " " (resistance)	36.5	48.2	—	34
" rotor copper (thermometer)	24.5	38.5	34	32
" " " (resistance)	33	32.6	—	35
" rotor core	24	34	28	25
Amperes per phase	312	390	341	312
Air temperature, deg. cent.	18	18.5	16	21

TABLE II

INDUCTION MOTOR—PHASE-WOUND ROTOR

Rating: 300 h.p., 50 cycles, three-phase, 550 volts, 16 poles, 367 rev. per min.

Losses.

Primary copper	5950 watts
Secondary copper	5050 "
Core loss	4900 "
Bearing friction and windage	3200 "
Total	19,100 watts

TEMPERATURE DATA

Kind of load	Actual	Circulating current
Length of test in hours	3	2
Volts	550	158
Per cent full-load amperes	128.5	128.5
Rise, stator core, deg. cent	25	38.5
" " copper (thermometer)	23.5	36.5
" " " (resistance)	30.1	42
" rotor " (thermometer)	23.5	30.5
" " " (resistance)	25.2	38.5
Amperes per phase	373	372.5
Air temperature, deg. cent	20	30.5

TABLE III

INDUCTION MOTOR—SQUIRREL-CAGE ROTOR

Rating: 300 h.p., 60 cycles, three-phase, 2200 volts, 6 poles, 1160 rev. per min.

Losses.

Primary copper	4125 watts
Secondary copper	7500 "
Core loss	9140 "
Bearing friction and windage	4000 "
Total	24,765 watts

TEMPERATURE DATA

Kind of load	Actual belted	Circulating current
Length of test in hours	11½	2
Volts	2196	326
Per cent of full-load amperes	103	129
Rise stator core deg. cent	40.5	29.5
" " copper (thermometer)	25	28
" " " (resistance)	30.6	34.4
" rotor " (thermometer)	26.5	52.5
Rev. per min	1160	1155
Amperes per phase	71	88.8
Air temperature, deg. cent	23.5	23

TABLE IV

INDUCTION MOTOR—PHASE-WOUND ROTOR

Rating: 800 h.p., 60 cycles, three-phase, 2200 volts, 26 poles, 272 rev. per min.

Losses.

Primary copper	10,500 watts
Secondary copper	10,000 "
Core loss	14,000 "
Bearing friction and windage	7,700 "
Total	42,000 watts

TEMPERATURE DATA

Kind of load	Actual	Circulating current
Length of test in hours	7½	7½
Volts	2260	456
Per cent full-load amperes	126	102
Rise, stator core, deg. cent	42.5	36
" " copper (thermometer)	36.5	37
" " " (resistance)	44.5	41
" rotor " (thermometer)	26.5	50
" " " (resistance)	28	48.6
" " core	24.5	43.5
Amperes per phase	266	214
Air temperature, deg. cent	16.5	23

TABLE V

INDUCTION MOTOR—PHASE-WOUND ROTOR

Rating: 1600 h.p., 25 cycles, three-phase, 6400 volts, 6 poles, 492 rev. per min.

Losses.

Primary copper	17,300 watts
Secondary copper	18,200 "
Core loss	13,200 "
Bearing friction and windage	18,000 "
Total	66,700 watts

TEMPERATURE DATA

Kind of load	Actual		Circulating current	Rotor excited with d-c. and stator short-circuited	
Length of test in hours	5½	5½	6½	7½	8
Volts	6360	6300	950	0	0
Per cent full-load amperes	102	130	104.8	100	125
Rise, stator core, deg. cent	24.5	29.5	18.5	19	28
" " copper (thermometer)	23.5	31.5	25	19	35.5
" " " (resistance)	34.3	48	30	30	49.5
" rotor " (thermometer)	23	28	32.5	24	37.5
" " " (resistance)	28.5	35	34	—	62
" " core	19	20	25	16	26
" collector	22	22	22.5	23.5	31
D-c. volts on secondary				43	58
D-c. amperes in secondary				487	643
Air temperature, deg. cent	21	23	23.5	21.5	21

Table I. This is a fair example of the results of this method. A comparison of columns 1 and 4, run with the same current input, shows remarkably close results for a compromise method. Any slight inaccuracies which may be noted are due to using commercial test results and to a policy on the author's part of avoiding carefully edited laboratory readings.

Table II. In this machine, operated on 50 cycles, can be noted the tendency for the high rotor frequency to heat up the rotor and through it the complete machine. It will be noted that the test was at approximately 28½ per cent overload.

Table III. This test was at 60 cycles, and while an actual load of 103 per cent is compared with a compromise at 129 per cent it can be seen that the rotor on the compromise test ran at a higher temperature than would be the case with the same amount of actual load.

Table IV. This case shows the extreme variation of the compromise method and was on a machine where the depth of the rotor conductors was sufficient to magnify considerably the eddy current loss due to secondary currents at a frequency of approximately 120 cycles.

Table V. This is an interesting comparison and shows the results of compromise tests made by two methods, enumerated as (2) and (5) above, and the performance of the same machine under actual load. The results of all three tests were satisfactory, but the compromise results were, of course, secured with considerably less effort and expense than was true in the case of the actual load tests.

Conclusions

From these considerations are drawn the following conclusions:

1. That the employment of a compromise method of making temperature runs on induction motors of large capacity is in many cases desirable and necessary.

2. That the method outlined above as method (5) gives results which are always "safe" and which are in general a close approximation to the actual temperatures.

3. That it is desirable that the Standardization Rules of the American Institute of Electrical Engineers should recognize the various methods of conducting such compromise tests, together with their reliability and limitations as applied under varying conditions.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

LOAD TESTS ON TRANSFORMERS

BY J. J. K. MADDEN

Load tests on transformers may be conducted in several ways, all of which are intended to approximate as nearly as possible the operating conditions of the transformers, so far as temperature rise is concerned.

A run with actual load might be made by using water rheostats, but as this would be very expensive, some form of motor-generator method is ordinarily used, which will give approximately the same heating.

Fig. 1 shows connections for testing two similar single-phase transformers by the "motor-generator" method. The low-voltage windings are connected in multiple, to which normal voltage is applied. An auxiliary transformer connected in series with the high-voltage windings supplies the impedance losses. The same method may be used for any even number of transformers, and load and excitation may be applied to the same windings or reversed from the order shown in the illustration. The rated voltage of the windings will determine the arrangement.

Fig. 2 shows connections for testing three similar single-phase transformers, or one or more three-phase transformers if delta-connected.

Fig. 3 shows connections for testing two three-phase transformers. The transformers may be connected either delta or Y, but some means of regulation on the loading side must be included so as to be able to balance the load current independently in each phase.

Fig. 4 shows the same connections as Fig. 1, except that the low-voltage winding has several independent circuits. Excitation

is applied to one winding only, and the loads are properly distributed by inserting reactance, if necessary, in the circuits so as to balance the loads carried by each winding.

Fig. 5 shows connections for testing two similar polyphase Scott-connected transformers. Excitation and load are applied to the three-phase side.

Fig. 6 shows connections for testing two similar single-phase

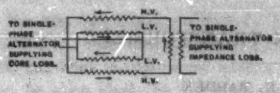


FIG. 1

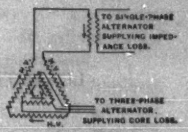


FIG. 2

transformers suitable for two-phase-three-phase operation. Load and excitation are applied to the windings used for the two-phase side, while an extra source of supply of current furnishes the 15 per cent additional current on the three-phase side. This will give the conditions obtained when the transformers are operated Scott-connected. This method is used on transformers which do not have the halves of the two-phase

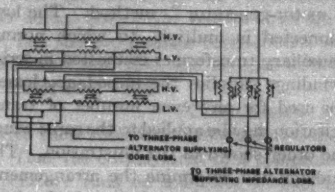


FIG. 3

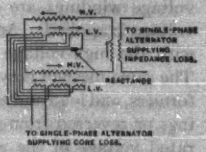


FIG. 4

windings connected in multiple. When the halves are connected in multiple both transformers should be connected as mains and should be furnished with load current equal to 115 per cent of their normal single-phase rating, as in Fig. 1.

The "motor-generator" or "opposition" method cannot, of course, be employed when one single-phase transformer is involved, and since the actual loading of such a transformer on water rheostats is not always feasible, it is the idea of this

paper to suggest, particularly, methods to be used on such a transformer. These methods must be such that they do not entail a great loss of power and yet approximate as nearly as possible the operating conditions ot the transformer.

These methods for testing single transformers may be classed as follows:—

a. Intermittent runs.

b. Ultimate open-circuit and short-circuit runs.

a. The principle of the intermittent run will be understood from the following considerations: The average temperature rise of oil depends upon the total watts loss in the transformer, and is independent of where the loss takes place. Therefore, if a loss equal to the total loss is intermittently placed in the iron and in the copper by alternating an over-voltage core loss run with an over-current impedance run, the oil should have a perfectly

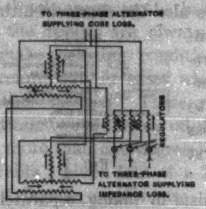


FIG. 5

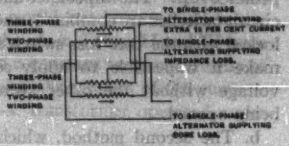


FIG. 6

normal rise. The temperature of the copper, however, would fluctuate between maximum and minimum values because during the core loss run the copper would be cooling towards the oil temperature, and during the impedance run, the copper temperature would be rising.

If, however, the integrated watt-hour loss over the complete cycle of the intermittent run is equal to the normal integrated copper loss for the same time, the mean of the maximum and minimum temperatures attained by the copper above oil would be equal to the normal copper rise above oil. If the time of each cycle is made small enough, the difference between the maximum temperature rise and the normal temperature rise above oil is small enough to neglect, in which case this maximum rise would be taken as the measure of the normal temperature rise of the copper. Actual tests here given show that if the

periods are reduced to five minutes, the difference between the two temperatures is less than the errors involved in testing. Moreover, the difference is on the safe side, since it always will tend to show temperature slightly greater than the normal.

It is also evident that if in the last copper run the time interval were cut in half, the maximum rise at the instant of shut-down would be much closer to the normal rise than if the run had been continued for the complete cycle.

Tests were made in which each run was continued until the top oil showed a constant temperature rise of not more than one degree within two or three hours. The run was then stopped at the end of a cycle or half period and the resistance of both windings taken.

Fig. 7 shows the connections for testing one transformer by the intermittent run method. Two oil switches are so arranged that when the one in the core loss circuit is closed the one in the impedance loss circuit is tripped, as is also the short-circuiting switch which is in use during the impedance run. The impedance and short-circuit switches are combined, and interlocked with the core loss switch so as to make it impossible to apply core loss voltage without the other switch first being opened.

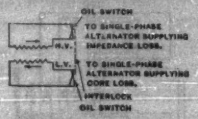


FIG. 7

b. The second method, which consists in taking, separately, ultimate short-circuit and open-circuit runs, is based on the idea that the temperature rises in windings and oil are directly proportional to the heat energy which is being dissipated. For example, if 100 watts total loss causes the oil to rise 10 deg. above air, a total loss of 50 watts should cause the oil to rise 5 deg. above a ir,and for the same reason, doubling the loss in the winding should double also the temperature rise of the winding above the oil into which it dissipates its heat.

Granting this assumption for a moment, suppose a transformer, in which the copper loss equals the core loss under normal load, attains an ultimate temperature rise of 40 deg. oil above air and 5 deg. copper above oil. Under an ultimate core loss run, the watts loss being only half the total, the oil rise should be 20 deg. above air, and the copper, being idle, would be at oil temperature. Similarly, an ultimate impedance run would give an oil rise of 20 deg. above air and a copper rise of 5 deg. above oil. The ultimate rise for either oil or copper for a load run is then obtained

by adding together the two rises resulting respectively, from the ultimate short-circuit and open-circuit runs.

Tests were made to prove the correctness of this hypothesis on 25- and 500-kw. transformers, and in both cases the values obtained by adding the temperature of the separate runs, gave values considerably higher than the normal run. In both cases, the sum of the ultimate oil rises obtained from the two is about 5 deg. greater than the oil rise obtained in an opposition run. The discrepancy may be due to the fact that the ability of the air in contact with the walls of the transformer tank to cool the transformer is not directly proportional to the temperature difference between the oil and the air, and also that the radiation from the tank increases more rapidly than the temperature rise.

Whatever may be the explanation, however, the tests given in Tables II and VI show conclusively that this method does not closely approximate the operating conditions of a transformer, but the results are always higher than those obtained under normal operating conditions. This method should be used, therefore, only in cases where it would not be expedient to use another method. These runs shown in Tables II and VI were continued until the top oil showed a constant temperature rise of not more than one degree in two or three hours of the run.

Table I gives data of a 25-kv-a. transformer operated under the following conditions:

1. Motor-generator method with a similar transformer.
2. Dead load on a water-box.
3. Voltage (corresponding to 371 per cent of normal core loss at 25 deg. cent.) for 2½ minutes and current (corresponding to 150 per cent normal impedance loss at 25 deg. cent.) for 7½ minutes.
4. Voltage (corresponding to 198 per cent of normal core loss at 25 deg. cent.) for 5 minutes and current (corresponding to 200 per cent normal impedance loss at 25 deg. cent.) for 5 minutes.
5. Voltage (corresponding to 139 per cent of normal core loss at 25 deg. cent.) for 7½ minutes and current (corresponding to 379 per cent normal impedance loss at 25 deg. cent.) for 2½ minutes.

In the above runs (3) (4) and (5) each cycle had a duration of ten minutes. It will be seen that the cyclic runs give results within 3 per cent of actual operating temperatures.

Table II gives ultimate open-circuit and short-circuit runs on the 25-kv-a. transformer, in which voltage and current corresponding to 25 deg. cent. losses were held as in Table I.

Table III presents the data of Table I and II in a different form, in order to point out the actual losses, core, copper and total, held on these tests.

Tables IV and V give data of a 500-kv-a. transformer, as follows:

1. Intermittent runs in which 199 per cent of normal impedance loss and 196 per cent of normal core loss were held for periods of 5, 10, 15, 20 and 30 minutes. The cycle was then reversed, *i. e.*, core loss first, followed by impedance loss.

TABLE I
Rating H-60-25 1100/2200-110/220

Cycles of run	Motor-generator run	Dead load run	Intermittent runs		
			2½ min. core loss 7½ min. imp. loss	5 min. core loss 5 min. imp. loss	7½ min. core loss 2½ min. imp. loss
Length of heat run—hours	22	17	24	20	24
Initial load applied.					
Core loss	145.4	145.4	539	288	302
Imp. loss	320.5	320.5	479	641	1212
Rise of high-voltage winding deg. cent.	41.3	40.5	41.4	39.5	42.1
Rise of low-voltage winding deg. cent.	43.2	41.2	42.1	40.2	43.5
Oil rise deg. cent.	29	29	31	27	32

NOTE.—Normal core loss at 25 deg. cent. = 145.4 watts.
Normal impedance loss at 25 deg. cent. = 320.5 watts.
All losses based on cold wattmeter readings.
Heat runs were made by holding voltage and current constant throughout each cycle of intermittent runs; also on motor-generator and dead-load runs.

TABLE II
RATING H-60-25-1100/2200-110/220

	Open-circuit run	Short-circuit run
Length of run—hours	10	18
Initial load applied.		
Core loss	145.4	——
Imp. loss	——	320.5
High-voltage wind. rise in deg. cent.	8.8	30.8
Low-voltage wind. rise in deg. cent.	11.2	34.4
Oil rise in deg. cent.	9	24

See Note under Table I regarding losses.

In each case the cycles were equally divided, *i.e.*, 5 minutes impedance loss and 5 minutes core loss, etc. The percentages are based on normal wattmeter readings at ultimate full-load operating temperature.

2. Motor-generator method with a similar transformer.

Table VI gives open-circuit and short-circuit ultimate temperature runs on the 500-kv-a. transformer.

Table VII gives results of intermittent runs of 10, 30, and 60-minute cycles, the periods for each being half this time. These runs are in all respects similar to those of Table V, with the exception that the run was cut off at the middle point of the impedance period. These results are seen to be in very close accord with those secured on the motor-generator run.

TABLE III

RATING H-60-25-1100/2200-110/220

		Per cent normal	Per cent total normal	Per cent time	Per cent total energy normal	Cold normal core loss at 25 deg. cent	Cold normal impedance watts at 25 deg. cent.
Core loss	Intermittent runs 2½ min.	371	115.5	27.5	102	145.4	320.5
Imp. loss	7½ "	150	103	72.5	109		
Core loss	5 "	198	61.8	50	99		
Imp. loss	5 "	200	137.5	50	100		
Core loss	7½ "	139	43.4	72.5	101		
Imp. loss	2½ "	379	260	27.5	104		
Core loss	Motor-generator run	100	31.2	100	100		
Imp. loss		100	68.8	100	100		
Core loss	dead load run	100	31.2	100	100		
Imp. loss		100	68.8	100	100		
Core loss	Open-circuit run	100	31.2	100	100		
Imp. loss		—	—	—	—	—	—
Core loss	Short-circuit run	—	—	—	—	—	—
Imp. loss		100	68.8	100	100		

All percentages based on 25 deg. cent. wattmeter readings.

Heat runs were made by holding voltage and current constant through each cycle, also for ultimate runs.

Table VIII presents the data of Tables IV to VII inclusive, in a different form in order to point out the actual losses, core, copper and total, used in these tests, in comparison with the normal.

In order to secure more reliable results, these two types of runs were made on two transformers, differing widely both in capacity and in the proportioning of losses. While the 25-kv-a. core and copper losses are proportioned 1 to 2.2 respectively, the 500-kv-a. losses are approximately 1 to 1.1.

It will be noted that these tests were conducted on self-cooled, oil-insulated transformers, but there is no apparent reason why such runs would not also be approximately correct for other types. It will be interesting to have the assumption checked on other types of transformers.

Referring to the intermittent runs, it is seen that in the case of

TABLE IV
RATING H-60-500-11000-2300

Cycles of run	Intermittent runs				
	5 min. imp. loss 5 min. core loss	10 min. imp. loss 10 min. core loss	15 min. imp. loss 15 min. core loss	20 min. imp. loss 20 min. core loss	30 min. imp. loss 30 min. core loss
Average length of runs—hrs.	5	6	6	5	4
Load applied.					
Core loss	6930	6930	6930	6930	6930
Imp. loss	6335	6335	6335	6335	6335
Rise of high-voltage winding in deg. cent	53.5	53.9	50.9	49.9	48.3
Rise of low-voltage winding in deg. cent	48.6	48.0	49.5	55.4	52.8
Rise of oil in deg. cent	50	50	50	50	49

NOTE.—The rises are averages of two or three runs.
Normal core loss at 74 deg. cent. = 3540 watts.
Normal copper loss at 74 deg. cent. = 3175 watts.
All losses based on hot wattmeter readings.
Heat runs were made by holding wattmeter readings constant throughout each cycle.

the 25-kv-a. transformer, a specified voltage and current were held constant, while on the 500-kv-a. unit watts were held constant. Excluding the question of stray losses, the two methods agree in applying the proper loss to core and copper respectively. However, due to the fact that stray losses are affected by temperature at a different rate from the resistance losses, when current is held constant, the proper value of losses will not be present at ultimate operating temperatures. On the other hand, due to the fact that stray losses increase at a less rate than the resistance loss, with increasing current, when watts are held constant, the losses at ultimate operating temperature are not

TABLE V
RATING H-60-500-11000-2300

Cycles of run	Intermittent runs					
	5 min. core loss 5 min. imp. loss	10 min. core loss 10 min. imp. loss	15 min. core loss 15 min. imp. loss	20 min. core loss 20 min. imp. loss	30 min. core loss 30 min. imp. loss	Motor-generator run
Average length of heat run hours	12	6	5	10	6	13
Load applied.						
Core loss	6930	6930	6930	6930	6930	3540
Imp. loss	6335	6335	6335	6335	6335	3175
Rise of high-voltage winding in deg. cent	56.1	57.1	57.5	59.4	62.8	53.6
Rise of low-voltage winding in deg. cent	46.7	52.0	52.2	54.3	58.5	45 9
Rise of oil in deg. cent	50	50	50	50	50	50

NOTE.—See Note, Table IV.

TABLE VI
RATING H-60-500-11000-2300

	Open-circuit run	Short-circuit run
Average length of run, hours	24	12
Load applied.		
Core loss	3540	——
Imp. loss	——	3175
Rise of high-voltage winding in deg. cent	27.8	32.5
Rise of low-voltage winding in deg. cent	28.2	34
Rise of oil in deg. cent	31	25

NOTE.—See Note under Table IV regarding losses.

TABLE VII
RATING H-60-500-11000-2300

	5 min. core loss 5 " imp. "	15 min. core loss 15 " imp. "	30 min. core loss 30 " imp. "
Average length of run—hours	8	8	13
Load applied.			
Core loss	6900	6900	6900
Imp. loss	6340	6340	6340
Rise of high-voltage winding in deg. cent	50.4	52	53.9
Rise of low-voltage winding in deg. cent	44.1	44.8	46.3
Rise of oil in deg. cent	48	48	48

See Note under Table IV

The above heat runs were shut down and temperatures, etc. measured at the middle point of the last impedance period.

TABLE VIII

RATING H-60-500-11000-2300

		Per cent normal	Per cent total normal	Per cent time	Total energy per cent normal	Cold normal core loss at 26.5 deg. cent	Cold normal impedance watts at 25 deg. cent.	Hot normal core loss at 74 deg. cent.	Hot normal impedance watts at 74 deg. cent.
Core loss	Intermittent	196	103	50	98	3770	2710	3540	3175
Imp. loss	run	199	94.1	50	99.5				
Core loss	Motor-generator	100	47.3	100	100				
Imp. loss	run	100	52.7	100	100				
Core loss	Open-circuit	100	47.3	100	100				
Imp. loss	run	—	—	—	—	—			
Core loss	Short-circuit	—	—	—	—				
Imp. loss	run	100	52.7	100	100				

NOTE.—All losses based on hot wattmeter readings.

Heat runs were made by holding wattmeter readings constant through each cycle, and also for ultimate runs

distributed exactly as under normal conditions, although the total may be correct. It would appear that the latter method is the better of the two, although no serious errors will probably result from either, except possibly in the case of transformers possessing very large stray losses.

The two sets of runs will also be seen to differ as to the relative duration of core and copper periods. In the case of the 500-kv-a. machine, the complete cycle was divided equally between core and copper, viz., double losses were held for half the cycle on core and copper respectively. On the 25-kv-a. machine, the complete cycle was divided unequally between core and copper, the losses in each case being inversely proportional to the time. Although, from a general standpoint, it would be simpler and more convenient to specify equal core and copper periods, yet cases will often arise where it will be of considerable advantage to increase either the core or copper period, corresponding to either high flux or current densities in the particular design in question. This is due not only to possibility of abnormal local heating, but also to possible errors introduced, for instance, as a high exciting current on the core loss period. In such a case, it is practicable to eliminate the error by reducing the energy loss on copper period by the amount held on copper in core loss period. Similarly, in case of appreciable core loss on copper loss period, reduction in energy loss on core period can be made. The error due to high exciting current can also be eliminated by an increase in frequency.

In the case of the 500-kv-a. unit, various periods for the complete cycle from ten minutes to one hour were tried out, all runs giving fairly good results. Although, from the standpoint of switching, etc., it is of advantage to employ cycles of considerable duration, care must be taken not to jeopardize the transformer by local heating in any part.

It will be seen from the tabulated data that more consistent results were secured by cutting off the load on the last cycle at the middle of the copper period than by cutting off at the end of the cycle. This is, of course, much more correct, although somewhat in error due to the fact that the rate of increase in temperature with a given load diminishes with the time the load is applied. If desired, still greater refinement may be secured by making a change to shorter cycles, say of ten minutes, at the middle point of copper period, when constant cyclic conditions have first been reached.

Recommendations

Since the "motor-generator" method of making heat runs which has been universally used, is satisfactory, this method is recommended, whenever more than one single-phase transformer or when one or more three-phase transformers are available.

Based on the above discussion, and tests presented in the attached tables, the following method is recommended for obtaining as near as possible the normal temperature rise under operating conditions of one single-phase transformer.

By suitable means, raise the transformer windings to estimated operating temperature, after which measure normal core loss and normal impedance loss. Select such a time for the cycle, say thirty minutes, as will avoid excessive local heating. Divide the cycle into two periods, which are inversely proportional to watts loss to be held in the respective periods. Unless considerations such as abnormal exciting current (which can usually be obviated by raising the frequency) prevent, hold total normal loss of machine first on core and then on copper. Alternate the core and copper periods until the temperature of the cooling medium is constant. Cut off run at middle point of copper period, and record temperatures and resistances. Closer refinement may be obtained by reducing the length of the cycle to, say, ten minutes, at the end of the run noted above.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913, By A. I. E. E.

SOURCES OF ERROR IN TRANSFORMER TESTS

BY W. M. McCONAHEY AND C. FORTESCUE

In order to obtain accurate results in making transformer tests, it is necessary to make all measurements and tests very carefully, and to be able to pick out and eliminate all errors or sources of error. Some errors can be avoided, while others are of such a nature that they must necessarily be included in the measurements and can be corrected later. Only those errors or sources of error that have an appreciable effect upon the results should be eliminated, since to include all would be introducing laboratory methods into commercial testing, thus unreasonably increasing the time and cost of making tests without securing any useful results.

Instruments. Instruments should be selected to give a good scale deflection, as small errors in observation give a greater percentage error for small deflections than for large. They should be calibrated at regular intervals, and if at any time it is suspected that they have been subjected to abnormal usage, their calibration should be checked at once. Care should be taken that they are not used beyond their capacities, as in this way the calibration may be changed, or they may be damaged.

It is best to avoid the use of instrument transformers wherever possible, but when it is necessary to use them, they should be calibrated at the proper frequency, with loads equivalent to the instruments with which they are to be used.

Instruments should be located so as not to be influenced by stray fields. Neglect of this precaution may, in many cases, result in the introduction of serious errors. Careful note should be made of the way in which the instrument is connected in the

circuit so that, when necessary, correction can be made for the losses that occur within the instrument itself.

Tests. Complete tests on transformers ordinarily include:

Ratio,
Polarity,
Resistance,
Iron loss and magnetizing current,
Copper loss and impedance,
Heat run,
Over-potential test,
Insulation test.

Each of the above tests will be considered separately.

Ratio. There is little difficulty in measuring the ratio of large power transformers. The number of turns is comparatively small and almost any convenient voltage may be used. Great care, however, must be used in order to get the correct ratio of small high-voltage transformers, and particularly those to be used with instruments. With the latter it is necessary that the ratio be correct within very narrow limits or the accuracy of the instrument readings will be seriously affected.

In measuring the ratio of small transformers with voltmeters in the ordinary way, it is necessary to apply practically normal voltage in order to secure accurate results. If only a small percentage of normal voltage be used, the drop due to the load of the measuring instrument alone will introduce considerable error. The most satisfactory way of measuring the ratio of such transformers is by paralleling them with standards of known ratio that have been specially designed with a large number of taps covering a wide range with very small steps. With a testing set of this kind, the ratio can be determined with a close degree of accuracy.

Polarity. The polarity of single-phase transformers is easily measured and requires no special precautions.

The polarity of three-phase transformers involves the relations between the phase displacement and the direction of the voltages at the terminals of the high-tension and low-tension windings, and the necessary measurements should be made to determine these relations. This can be best done by connecting one of the high-tension to one of the low-tension terminals and impressing a convenient three-phase voltage across either winding and measuring all the combinations of voltages among the six terminals. From these, and a knowledge of the connections of

the windings (whether delta or star), a voltage phase diagram showing the polarity can be constructed easily.

Resistance. The utmost care should be used in measuring resistance in all cases where it is used as a basis for determining the temperature rise. In measuring the cold resistance, it is just as important to know the actual temperature of the winding at the time the measurement is made, so as to get a correct basis from which to calculate the temperature at the end of the heat run.

Where the transformer is standing in the air, several thermometers should be placed in close contact with the coils at several points and, before making the measurement, time enough should elapse so that the temperature of the coils will be within a degree or two of that of the surrounding air. In order to secure the best results, the measurements should be made when the air temperature is steady, or at least showing very little fluctuation.

Where the transformer is in oil, it should be allowed to stand until thermometers show a practical agreement between the temperature of the windings and that of the oil.

In making the measurements, the readings should be taken as quickly as is consistent with accuracy, and the current should be small enough to avoid any appreciable heating of the windings. The temperature of the windings, as shown by the thermometers, should be carefully noted at the same time.

Resistances can be measured most satisfactorily with a Wheatstone or a Kelvin bridge, the former being used for the higher, and the latter for the lower resistance. The resistance to be measured is generally known approximately, so that the bridge can be set fairly close to the correct point beforehand, and the time taken in getting the correct setting, when measuring the resistance at the end of the heat run, can be made very short.

Iron Loss and Magnetizing Current. The iron loss is a function of the frequency, the voltage and the voltage wave form. The frequency and voltage can be determined easily, but this is not true of the wave form.

Since the iron loss may be appreciably decreased or increased, according to whether the voltage wave form is peaked or flattened, it is very desirable to have some satisfactory method of getting the proper correction to be applied to the wattmeter reading, so that the corrected result will be the same as would have been secured if the voltage wave had been of the sine form. It is possible to arrive at this by taking an oscillograph curve of

the voltage wave when the iron loss is being measured, and analyzing and comparing it with the true sine form. This is a tedious operation, and one not suitable for commercial testing. A very satisfactory way of making the correction easily and directly is by using the iron loss voltmeter. This instrument gives at once the necessary correction without any calculation, and is therefore exceedingly useful for making iron loss measurements.

If the generator used in measuring the iron loss is large enough so that it is only lightly loaded, and if its voltage wave closely approximates the sine form, there will be very little wave distortion, and the correction to the wattmeter reading will be negligible. In order to make sure of this, however, it is best to use the iron loss voltmeter in all cases.

In a transformer having a large magnetizing current, the I^2R loss in the winding during the iron loss measurement may be appreciable. This loss is constant at all loads, and may therefore be properly included in the iron loss.

Due to the voltage drop in the primary winding, the induction in the iron will be slightly decreased in going from no load to full load, thus tending to decrease the iron loss slightly. On the other hand, the path of the leakage flux about the windings lies partly within the iron, and this may tend to increase the iron loss under load. On the whole, the net difference is negligible, and the iron loss may be considered the same at full load as at no load.

Copper Loss and Impedance. In making copper loss and impedance measurements, care should be taken to see that the frequency is correct and that practically no increase takes place in the temperature of the windings during the measurement.

The frequency affects the eddy current loss in the copper, and also the reactance, which varies directly with it.

Since the copper loss varies with the temperature of the windings, correct results can only be secured by maintaining the temperature at a practically known value during the measurement. This is secured by placing thermometers in close contact with the windings and letting them remain there until they show a steady temperature, and then taking the readings as quickly as possible.

Knowing the temperature of the windings at the time the readings are taken, the copper loss for any other temperature can be calculated with very little error, except where the eddy current loss is very large. In the latter case, it is best to take the copper loss at or near the temperature desired.

Distorted wave form of e.m.f. has very little effect upon copper loss or impedance, unless the distortion is very bad.

Heat Run. The heat run is made chiefly to ascertain the temperature rise under given load conditions.

In getting the temperature rise by resistance, great care must be taken in making the measurements, cold and hot, as discussed under "Resistance." Care must also be used in getting the temperature of the cooling medium or water.

For oil-insulated water-cooled transformers, the surrounding air has some effect upon the cooling, but it may be neglected. The temperature of the ingoing water is taken as the basis for calculating the temperature rise. The source of the water supply is generally such that its temperature remains practically constant during the heat run, so that the principal points to be observed are to see that a thermometer is placed in the ingoing water; that its readings are carefully recorded at regular intervals; that the flow of water is kept constant, and that practically an equal amount of water flows through all parallel coils. At the end of the heat run, the flow of water and the power should be shut off at as nearly the same instant as possible.

For air-blast transformers, the temperature of the air in the pit is the basis for calculating the temperature rise, and it should be maintained at a practically steady value during the heat run and particularly near the end. The dampers should be adjusted to give the proper flow of air, which is generally such as will show a temperature rise of 11 or 12 deg. in passing through the transformer. In shutting down at the end of the heat run, the air blast and the power should be shut off at the same instant.

In making a heat run on an oil-insulated self-cooling transformer, its temperature is determined by that of the surrounding air in the room. The room temperature is always a more or less variable quantity and hard to control, and should therefore be given careful attention. The room should be well ventilated, but strong air currents should be avoided. A steadily rising or steadily falling air temperature towards the end of the heat run introduces an error into the determination of the temperature rise that is not easy to eliminate. A satisfactory way to correct for the error is to have an unloaded transformer standing nearby and use the variation in the resistance of its windings as a basis for the correction.

Oil-insulated self-cooling transformers, when on heat run, should be separated by a space approximately equal to the width

of the tanks. Thermometers should be placed about the transformers at a height that can be read conveniently, and far enough away not to be influenced by the radiation of the heat. This will generally require a distance of six feet (1.8 m.) or more from the transformers.

It has been the rule, heretofore, to make a correction of one-fourth of one per cent in the temperature rise, as calculated from the resistance, for each degree of variation of air temperature from the standard of 25 deg. Experience, however, seems to show pretty conclusively that this is in error and that, for all practical purposes, no correction should be made.

Insulation Test. Before making this test, all the terminals of the high-tension winding, and also all those of the low-tension winding, should be connected together. Also, while testing between the high-tension and low-tension or ground, the low-tension should be connected to ground. Otherwise, in testing between the high-tension and ground, dangerous stresses may be set up between the low-tension and ground far in excess of any that may occur in service, and a breakdown may result.

In making tests of about 50,000 volts or more, a spark gap should always be used. Because of the voltage rises that take place, the ratio of primary to secondary voltage of the testing transformer cannot be taken as equal to the ratio of turns, so that, without the spark gap, there is no measure of the actual testing voltage. A high resistance, sufficient to limit the flow of current to a small amount, should be placed in series with the gap.

Air bubbles in the oil about the transformer may be a source of serious trouble, and therefore, if there is any indication of their rising to the surface of the oil, the insulation test should not be applied until they cease. The test should be made immediately following the heat run, while the transformer is warm.

Over-Potential Test. This should be the last test applied. With high-voltage transformers, in particular, care should be taken to see that all terminals, connectors, etc., are in proper place. The frequency used should not be higher than is necessary to keep the magnetizing current within reasonable limits.

It is necessary in this test, also, that there be no indication of air bubbles in the oil.

GROUP III PAPERS

(Pages 649 to 708)

Method of Testing Apparatus for Performance

(a) GENERATORS AND INDUCTION MOTORS

Comparison of Methods of Loading Large A-C. and D-C. Generators and Synchronous Converters for Factory Temperature Test, by F. D. Newbury.

Comparison of Methods of Making Load Tests on A-C. Generators and On Induction Motors, by E. F. Collins and W. E. Holcombe.

Notes on Methods of Making Load Tests on Large Induction Motors, by A.M. Dudley.

(b) TRANSFORMERS

Load Tests on Transformers, by J. J. K. Madden.

Sources of Error in Transformer Tests, by W. M. McConahey and C. Fortescue.

DISCUSSION ON GROUP III PAPERS—(METHODS OF TESTING APPARATUS FOR PERFORMANCE). NEW YORK, FEBRUARY 28, 1913.

(a) GENERATORS AND INDUCTION MOTORS

A. E. Averrett: I would say in regard to the results in the Collins and Holcombe paper, that I made some tests at the same time, and the results obtained with the first two motors (two 20-h.p. motors) were somewhat erratic; one of the motors was somewhat unusual, in that the rotor had a completely closed slot. We ran these tests through in a hurry and I believe the results ought to be discounted.

The 50-h.p. 900-rev. tests show remarkably close results, 24 deg. by the actual load, and 26 deg. by the approximation method. The next test, the 100-h.p., shows very close results, 24 deg. by the full load, and 26 deg. by the approximation at normal load, and at 25 per cent overload it shows 34 deg. rise by load and approximation.

The next machine, 250-h.p., was a machine we selected in the test which we were in a hurry to ship, and we did not test it as carefully as it should have been tested. Before we used this method at all, several years ago, Mr. Collins conducted a number of careful tests, running over six or seven machines, and sufficient time was taken to test them out thoroughly. The agreement between the compromise tests, as we called them—that is, the full-voltage, no-current test, and the full-current, low-voltage test—was very close, and we thought that it was as safe as duplicate tests under approximately full-load conditions. They were remarkably close, and as a result we adopted that method for big machines.

This seems to hold on a wide range of machines, machines with a high core loss and low copper loss, or the reverse.

Commenting on Mr. Dudley's paper, the reverse rotation method; on the first test the normal rise was 25 deg. and on the circulating current method, the reverse rotation method, I believe he calls it, it was 38 deg. There is a considerable discrepancy. That machine, probably, is a machine with a small core loss. It is a wound rotor and undoubtedly the eddy losses in the copper at double frequency must have developed to heat the machines up so much.

In the next table the reverse is the case, that is, the core loss is large; I suppose that should be correct; they have given it different currents—the actual load temperature is quite a little higher than the circulating. In the next group the actual is a little higher than the circulating. In the table which follows, the actual is higher than the circulating, and it seems to me, from my own experience, that this reverse rotation method will hold closely in a machine where the losses are largely copper, and the core loss very small, but in a machine where there are no eddies, and where the core losses are high, I

do not see how it can hold. It happens in the average run of machines that the copper loss is quite a little higher than the core loss, and undoubtedly the double frequency in the secondary teeth, even at low density, does give enough additional loss to approximate full-load conditions; but I believe it is only applicable to a very narrow range of machines.

R. B. Williamson: A load obtained by means of synchronous motors running idle, and operating the generator at zero power factor, makes about as satisfactory a compromise test as can be obtained.

In it the conditions are worse than under actual load, because the field current is greater, but it shows what the heating will be under the worst possible conditions. This method can be made to approach actual conditions closer by using alternately leading and lagging currents, but this makes the test more complicated.

Where this test cannot be applied, the next best is the open-circuit test at such over-voltage as to make the total losses in the machine approximately equal to what they would be under load. The distribution of the losses is different, but it gives a test of the field heating, and also some idea as to the core heating under actual load. A test of this kind is especially useful for turbo-generators where most of the loss is in the core, and in windage and friction, and where the stator copper losses are comparatively small. A short-circuit test, by itself, does not show much, unless there happens to be local heating due to stray losses of some kind.

R. E. Hellmund: With regard to induction motors, I agree with Mr. Averrett that the method of testing induction motors with reversed rotation can only give results with machines where the core losses are comparatively low. However, the large majority of machines are of that kind, and the test is so convenient, as compared with others, that I think it should be legalized within certain limitations. We have used it a good deal, and although we know its limitations, we find it a cheap and convenient test for many cases. Altogether, in induction motors, any heat test that takes principally into account the copper losses will be satisfactory in most cases, due to the fact that in all but high-speed machines the core losses play a comparatively small part in the heating, except possibly in motors with very high speeds. In the ordinary run, the core losses are a small percentage of the total losses; but not only that, the seat of the core losses is in such close contact with the frame and other large cooling parts that often a doubling of the core losses in medium- and low-speed machines can hardly be found in the heating, while any additional copper losses appear rather rapidly.

B. G. Lamme: I will say something on the general subject of testing. The manufacturers of electrical apparatus make what might be considered four different kinds of tests. In the first

place, a test is sometimes made which is primarily for the purpose of obtaining data for design purposes. Such tests may be made on exceptionally good machines upon which the manufacturer wants special data. These tests are of no particular advantage to the purchaser, or to anyone, in fact, but the designer.

A second kind of test is that made by the manufacturer's engineers, to determine whether the machine meets a specified guarantee. A third set of tests is what might be called a witness test, to prove to the customer that the machine meets the guarantee. The second and third kinds of tests should really be covered by one test, but, in many cases, this apparently cannot be done, as the test which indicates to the designer that the machine is all right does not always appeal to the customer as being a satisfactory test. A designing engineer and the customer's engineer look at the machine from two different view-points. The designer judges the test from his experience with similar kinds of machines upon which he has obtained data, and he bases his opinion partly on experience. On the other hand, the witnessing engineer wants full proof that the individual machine being tested meets the guarantees, although this covers a lot of work which has already been carried out by the manufacturers many times on similar machines. What we would like to get is some recommended standard test or tests which would eliminate a lot of this double testing and the disagreements which naturally accompany it.

A fourth class of tests may be called routine tests. For instance, if a great number of duplicate machines are made, only one of these may be tested completely, while, on the remainder, certain tests are made which show only certain characteristic data, which, compared with the more complete test, indicate that the machine is necessarily a practical duplicate in performance.

Leo Schuler: I want to ask whether it is the intention to make this equivalent test a part of the Standardization Rules. I think that would be rather dangerous. There are natural differences between the results obtained by these equivalent tests and by the real load tests. I think, however, it would be a very good thing for you to make an appendix to your Standardization Rules, in which certain methods of artificially loading machines and transformers are recommended, and in which the probable sources of error are indicated. This would facilitate and strengthen the position of the manufacturer if he could show under the authority of the American Institute of Electrical Engineers that the probable error would not be more than such and such an amount.

B. G. Lamme: I want to say that Mr. Schuler's statement represents exactly the attitude of the Revision Committee on this subject. The committee wishes to recommend, if possible, certain tests as the advisable ones, and to state the disadvantages and probable errors of each, so that in any test that is specified

and carried out, it will be known just what errors are liable to be found. At the present time, the difficulty lies in the fact that there is a continual disagreement over these errors in testing. If the fact can be brought out conspicuously that certain errors are inherent in our methods, it would eliminate some of our troubles.

E. I. Chute: The simpler the method of testing the more accurate and consistent will be the results obtained. Results that cannot readily be duplicated are oftentimes worse than useless, as they may lead to erroneous conclusions. The intermittent temperature tests proposed, while very pretty in principle, are quite difficult for a tester to conduct in such a manner as to duplicate results. Unless there is some very decided advantage gained by the suggested methods, and this seems contrary to our experience, the zero power factor test with over-excited field when possible, and the circulating current test in other cases, should be recommended.

Paul M. Lincoln: This question of substitute tests or compromise tests, is an important one to the manufacturer, because the tests, practically all of them, are made in his own shops where the facilities for testing are usually limited when it comes to the question of applying real power to the machines. The amount of power which can be so applied is limited, both on account of the fact that the power may not be available, and also on account of the fact that the method of application, such as is used in the final installation, is not usually available at the time of test. I am in perfect accord with the opinions which have been expressed to the effect that the best substitute test is one where the machine operates at zero power factor. That is the best substitute test, and is certainly one which will give as high temperatures as the machine will give at any other power factor load.

That is all very well for such machines as the manufacturer is prepared to load up in this manner, but the modern machine often goes beyond the ability of the manufacturer to supply the apparatus necessary for this test. When we are dealing with machines of 10,000 to 20,000 kv-a., most manufacturers are not prepared to supply loading-back facilities for so large capacity, and therefore it becomes important to have a test which we can substitute in place of the zero power factor test, and it is the effort to find such a test that has led to the paper by Mr. Newbury and also the paper by Messrs. Collins and Holcombe. The most hopeful line of investigation seems to point to some method of alternate open-circuit and short-circuit operation that will give results in heating, equivalent to the actual load test. The results so far reported would indicate that the alternating cycles of short circuit and open circuit will give a test which is sufficiently close to actual results to make it one which may be safely referred to in our Standardization Rules.

F. D. Newbury: I do not like to disagree with my colleague, Mr. Lincoln, but I must take issue with him in his statement

that the intermittent short-circuit or open-circuit test is to be placed next to the zero power factor lagging test. In my own experience I have found the direct-current circulating test to be preferable, for machines for which it is suitable, to any other test. The only limitation to the use of the direct-current circulating test is the presence of solid material in the rotor. There is, of course, a field, which is stationary, with respect to the revolving field, so that any solid material in the revolving part will have rather severe eddy currents generated in it. I think that is the explanation of the very high rotor losses shown in some of the tests given by Messrs. Collins and Holcombe. But that is a limitation that is easily foreseen, and the effect can be directly measured by observing the input to the driving motor with the direct current in the armature, and without the direct current in the armature, so it is a perfectly safe test to apply. You know when you can safely apply it, and when you cannot. The objectionable test is the one in which you cannot predict abnormal conditions and cannot, therefore, interpret results when you obtain them. The difficulty with the intermittent open and short circuit test, I think, is one that Mr. Chute brought out, which is the difficulty of exactly duplicating results and the lack of experience, so far, as to the proper relative open-circuit voltage and short-circuit current. In the large generator we tested, the core temperature was about 10 deg. higher by the intermittent test than by other available methods—the circulating or zero power factor methods. That indicates that the theoretical condition of equal losses is too severe a condition for that method of test, or at least, for certain generators. After it has been found that it gives erroneous results in one generator it raises the question as to its reliability in the next generator, and prevents its adoption at least until we have attained as large a number of years of experience with the method as we have with the other methods of testing.

Leo Schuler: We spoke a good deal yesterday about additional losses, or "stray losses" or "load losses," or whatever you might call them. Several very interesting papers have been presented upon this question, but, nevertheless, no simple and easy method has been suggested for calculating these additional losses for every machine, and calculating them so as to convince the consulting engineer. Even if Mr. Lamme is going to guess this additional loss, I do not know whether the consulting engineers will be convinced by that method. If you make an equivalent test of any kind whatever, it will never be possible to take these additional losses into true consideration, because you do not know them, and this will always be a drawback in these equivalent tests.

A. J. Porskievies: In two-phase machines it is not always feasible to get open delta direct-current heat runs because circuits may not be arranged to provide for circulating currents. Also in single-circuit machines it may be difficult to arrange for

circulating currents, both from electrical and mechanical standpoints. There are enough two-phase machines in demand to give this consideration some weight.

Carefully made open- and short-circuit heat runs ought to give reliable results provided the equipment does not permit of the circulating method.

F. D. Newbury: The point in regard to two-phase and three-phase generators is taken care of in either the zero power factor test or the direct-current circulating test. Of course, the method of test is more familiar to us in the case of three-phase machines, because all large machines at the present time are three-phase. The only condition necessary for the application of the direct-current circulating test is that you can form a closed circuit, and open this at a point at which the voltage is zero, for the introduction of the direct current. This can be done with a rectangular connection in a two-phase generator as well as with delta connection in the three-phase, so that the direct-current method is just as applicable to two-phase as three-phase.

As to the point brought out by Mr. Schuler, in regard to the stray losses; while we cannot measure these stray losses, some of these methods do take them into consideration. In the zero power factor method all of the stray losses are present, except the difference due to the different flux distortion at zero power factor and operating power factor. Of course, the distortion is less—strictly speaking, there is no distortion at absolute zero power factor. In some generators, notably some low-speed engine type generators, we can obtain higher temperatures on energy load than at zero power factor.

Leo Schuler: I do not consider the zero power factor method an equivalent. I think it is the real method.

F. D. Newbury. I have no comment, then.

Alexander Gray: Regarding the direct-current circulating test; I used to think it was a very good one until I came across a machine recently which on the test floor had a temperature rise of 40 deg. cent., but, when put in operation, got so hot in the center that the machine had to be rewound. It so happened that the design was faulty, because the machine had deep conductors and a core 32 in. (81.28 cm.) long, and the direct-current circulating power test did not disclose the eddy current losses or the hot spots in the machine. It is for such large machines that we want an equivalent test. Moderate size machines can be tested by the zero power factor method, but large waterwheel and turbine units take a large amount of current from the power house, and must be tested by some other method.

B. A. Behrend: A very convenient test in connection with the testing of multipolar alternating-current generators was suggested by me ten years ago. It consists in the division of the field circuit into two circuits of equal number of poles. Hundreds of these tests have been made on machines of all sizes ranging from 50 kw. to 5000 kw., and they have been satisfactory. The

method has been termed the "split-field method," and it is fully described in a paper read before the International Electrical Congress at St. Louis in 1904. It is entirely practicable. For instance, you can take a machine like the 40-pole Manhattan generators, and, by tapping the field circuit in one point, and passing different currents through the two field circuits, you can obtain a zero power factor load on that machine. The heating is very nearly the same as under zero power factor. The method eliminates mechanical, vibration, as the armature reaction balances the strength of the magnetic poles. The regulation corresponds to a power factor of zero. The chief objection to all equivalent tests lies in the proper adjustment of the field excitation. If you want to use the direct-current circulating test you have to know what field excitation to use. If you want to use an intermittent test, a core loss test alternating with a short-circuit test, you must also know what short-circuit current and what excitation to use in both tests, and in order to know that, you require a knowledge of the zero power factor regulation, and a method for deducing from this zero power factor the regulation at other power factors under which you desire to make the equivalent test. With all these difficulties before you, I think you will agree with the chairman in his statement that it would be unwise to embody equivalent test rules in the Standardization Rules, because it would open up all doors to discussion and disagreement. I fear that in order to accomplish anything you will have to adopt Mr. Lamme's method, which I consider, personally, an ideal method, viz., the method of guessing, as I can guess a great deal better than most people can test, and so can Mr. Lamme, but we have difficulty in making others believe that we can do it.

R. B. Williamson: I believe that the short-circuit loss curve is the best indication we have of the various stray losses. These stray losses are due to a number of different effects, such as eddy currents in conductors and currents set up in unlaminated parts, particularly of enclosed machines, such as turbo-generators. Mr. Lamme brought up the point of the stray loss also bearing a relation to the core loss. If a machine has a poor core and a high open-circuit core loss it will be reflected in the short-circuit core loss curve. That is, a machine with a bad open-circuit core loss will also show a bad short-circuit core loss. The short-circuit core loss curve thus takes account of nearly all of these items entering into the stray loss, and as shown by Mr. Foster, the total short-circuit core loss checked up very closely with the measured stray loss.

In most open machines the stray loss is small if the machine is properly designed, and in machines where it is sometimes considerable, such as in turbo-generators, it can be easily shown that part of it exists in certain parts of the casing. It seems to me that if such losses are shown by the short-circuit loss curve they must be present on regular load. I would therefore be in

favor of taking the whole of the short-circuit core loss in estimating efficiency as being nearer the truth than the one-third part as recommended at present by the Rules.

F. D. Newbury: No method of loading, as such, will in itself bring out the internal heating; that must be secured by better methods of temperature measurement. I have had very deeply impressed on my mind this fact in connection with some large generators which were tested by the zero power factor method. They came through finely, and everybody thought they were good machines, and yet, when some of the coils were taken out, in order to ship the stator in halves, the interiors of some of the coils were found to be very seriously damaged by heat, so much so that the generators had to be rewound; and, to bring out a point mentioned by Mr. Wilson, a comparison of the short-circuit loss before they were rewound and after they were rewound did not indicate any material difference. It was simply a case where the armature conductors were supposed to have been laminated and insulated from each other, but in a few coils the insulation was defective. Certainly that cannot be detected by a method of loading, or in all cases by a method of temperature measurement.

H. M. Hobart: In substitute methods, one wants to get as nearly as possible to the same heating in each principal part of the machine as one gets when the machine is in regular service and it is carrying its rated load. One wants the same number of heat units per hour, or half hour, or ten minutes, developed in each part as under the conditions of rated load. By the intermittent open-circuit and short-circuit method you get exactly that, provided you make each cycle of operations occupy a sufficiently small number of minutes. In very large machines it is generally arranged to have the complete cycle of operations occupy fifteen or twenty minutes. But you can take even greater intervals and taper them off toward the end of the run into very short periods. In any case, I cannot see that there is any flaw whatsoever in this method, except that alluded to by Mr. Schuler and others, that there is a little uncertainty about the flux distortion under the different conditions, and that difficulty is met in all the other methods and sometimes to a much greater extent than in this method.

If in any case there is any startling discrepancy between the results obtained by this intermittent method and by any other method, the suspicion lies on the other method. However, the intermittent method has the disadvantage of requiring the expenditure of mental effort in planning the test in advance and this has usually served to bring it into disfavor. But certainly the time of an engineer is well spent in mapping out the scheme on paper, and ascertaining the appropriate conditions for the test. As an ultimate standard I cannot conceive of anything better than this test, where the power available is limited.

I do not believe that the difficulties of carrying out this test

are nearly so great as is at present thought; it is simply lack of experience and chronic aversion to anything new. I believe it only requires time for this scheme of testing to win out on its merits, but it seems to me a pity to wait for several years, for the natural process of evolution to bring this method to the front. When it was first brought to the attention of engineers, there was a great deal said about the loss of time in switching over from one connection to the other. That can be done practically instantaneously, as is now generally admitted. All sorts of other objections were brought forward, but now it seems to me the only one on which engineers fall back, is the fussiness of making these preliminary calculations, and this objection, it seems to me, is magnified unduly. I trust that careful consideration will be given to the merits of the alternate short-circuit and open-circuit tests.

Leo Schuler: I wish to endorse fully the recommendation which Mr. Hobart made with regard to his method. It is certainly a very excellent, and at the same time a very convenient method, and I can say that this method has been applied to a great extent, in the works with which I was connected. As, however, the short-circuit losses are fully taken into account by the Hobart, test the temperature measured in this way will be somewhat higher than that which could be expected in the real load run; this is, of course, all right for the shop test, but you must distinguish between the shop test and the official test, and if you have not much margin on the temperature allowed, then you would naturally hesitate to make this Hobart test as an official test.

Stuart L. Henderson: The intermittent short-circuit and open-circuit test does not work out very well from a practical standpoint on large machines, and it is on this type that the test should have its greatest application. The chief difficulty is to get reliable temperatures. During the time the machine is on short circuit the iron temperatures decrease and when on open circuit the copper temperatures decrease. This necessitates cutting down the time of the cycle towards the end of run to obtain uniform temperatures, and consequently a man does not have time to get around to read all the temperatures before the cycle is changed. This practically means putting a man on each thermometer to obtain satisfactory results.

J. J. K. Madden: The switching arrangement is not as difficult as would at first appear. Tests were made on a 500-kv-a. unit by the use of two interconnected switches, but it was unnecessary to adjust the field current when applied.

Charles P. Steinmetz: In considering the tests by alternate short circuit and open circuit, we must realize one feature. In all other tests it is always necessary to make a correction for the field excitation, which is higher or lower than that for full load. We alternate over-voltage runs at open circuit, with overcurrent runs at short circuit. Thus we have two independent

variables, and we are enabled to so select the over-voltage, the over-current, and the time period that not only the total losses during each cycle are equal to the full-load losses, but also the total losses in the field are identical with the full-load losses. Consequently you can obtain the correct field heating as well as the correct armature heating. This test seems to me to have considerable merit, and is often the only practical test available.

In regard to the alleged complexity of switching over to change open circuit to short circuit, and vice-versa, that requires two short-circuiting switches, one across the armature and one across the rheostat in series with the field. To operate two switches is not a very complicated matter. You will not have to adjust the field or effect any other adjustments. These adjustments are made before starting the test. We thus see that the switching operations are extremely simple. But whether the test is generally applicable or not, depends entirely on further investigation. There is a possibility that you cannot adjust the two independent variables at the values necessary to obtaining the correct heating by this kind of test. It may be that the excitation required in order to circulate the appropriate armature current on short circuit will give you a higher field heating than, taken in conjunction with the excitation on open circuit, corresponds to the same total heat per cycle of operations with normal load excitation. There are several limitations which have not yet been fully investigated; for a general method, this test has merits which require careful consideration.

F. D. Newbury: There was one point mentioned by Mr. Steinmetz, which was illustrated in the case of a machine we tested. In order to divide the loads between open circuit and short circuit, so that the total losses on test at any given instant would be equal to the total loss on energy load and also that the watt-hours would be equal to the watt-hours in a test under actual operation, we found that the field losses during the test were 30.65 kw. per hour. The same losses at 100 per cent power factor and full load were 19 kw., and under zero power factor, 46.5 kw., that is, during the intermittent loss the field loss was intermediate between what it would have been at 100 per cent power factor and at zero. In the test we made, I added all the short-circuit losses and the I^2 losses, which may account for the higher temperatures we obtained. But that brings up the point that the method requires some experience in order to determine the proper conditions so that the test results will check with actual load. That same disadvantage is present in all tests, except to a very minor degree in the zero power factor test, and in the zero power factor test it is a condition which can be corrected for with full knowledge.

H. M. Hobart: In connection with a lot of machines which I examined, it was impossible to get the field loss right, when the other two losses were right, but the field loss was not nearly so

far out as in the zero power factor test. If the field heating is perhaps 10 per cent higher than under normal conditions, it does not seem to me it is vital, you can easily correct it, whereas you cannot make a reasonable correction of what the field temperature would be in actual practise, when it has been tremendously over-excited as in the zero power factor test.

During the short-circuit period the loss can be different from what it is during the open-circuit period, so long as the loss in each part, in the course of a definite period of time, say one hour, is the same as in actual practise. It may be of interest to state that this intermittent open circuit and short circuit method of testing alternators is not new, but was described by Mr. Franklin Punga and myself in the *Electrical World* for April 22, 1905. I have again drawn attention to it in an article entitled "A Method for Testing the Heating of Large Alternators" in the *General Electric Review* for November, 1911. In 1905 I employed the method in testing some large three-phase generators.

Alexander Gray: It seems to be my misfortune always to get erratic results. In testing induction motors, it is very important to notice whether there is a pulley on or not. I remember particularly a small 20-h.p. motor, running at 1800 rev. per min., which was supposed to drive looms by means of four belts and two pulleys. A motor at that speed is, of course, a small dumpy machine and rather long. That machine, tested with a pulley, rose 42 deg.; tested with two pulleys, one on each side of the machine, it rose 28 deg. cent. I could guarantee that the machine if direct-connected so as to operate without pulleys would have a temperature rise of 50 deg. I want to offer the suggestion that motors should be tested, as far as possible, under conditions under which they are going to be run.

W. J. Foster: What occurred to me at first, at the mention of the pulley, is something I have seen in a great many machines, and this is a movement of the air axially, a movement caused by a mechanical connection simply, a thing even more simple than a pulley, and where the rise in temperature in the machine is due to the fact that that small influence overcomes the natural radial movement that would exist and causes a totally different flow of air, an axial movement. Undoubtedly many of you have run across this trouble. Therefore, when Mr. Gray mentioned placing the two pulleys on the machine, it seemed to me that he then had the motor in approximately the same condition it would be without any pulleys whatever. This may not have been the explanation in that particular case, but in certain cases I have known, it has been the cause of high temperatures.

Alexander Gray: I want to confirm Mr. Foster's remarks about alternators. An alternator is generally put on a heat run during the night and temperatures are taken in the morning. It is often found that when the men come in at seven o'clock in the morning and open the door, the method of ventilation of the alternator is completely changed, and the temperatures also

change, so that it is always advisable to take temperatures before the men come in. As to the effect of a belt, the effect might be as follows: In a long machine the stator coils stick out beyond the core for a considerable distance and the tendency is for the cooling air to strike the coils and be drawn back into the rotor again, and so become hotter and hotter. The action of the belt creates the same kind of pressure on one side of the pulley and a suction on the other, and tends to draw the hot air out.

S. S. Seyfert: I would like to make a suggestion regarding the loading of alternators. It seems possible to subject a machine to normal current and voltage conditions without incurring the difficulties encountered in the methods discussed.

I was thinking of a method similar to the so-called pump-back test on transformers. Normal voltage conditions may be obtained by running the machine at the proper speed and excitation and normal armature current conditions, by impressing across the phases, properly connected in series, a reduced voltage of *approximately normal frequency*. The armature currents would have no resultant motor or generator action. The prime mover would supply core and friction loss, and the reduced voltage source would supply the armature copper loss. The increased heating developed when direct current is used on the opened delta should not occur.

In case the armature phases could not be opened so as to be properly connected, a bank of transformers, equivalent in capacity to the largest unit tested, would be required.

Edgar Knowlton: *Open Delta Method.* This test has given very erroneous results when the three-phase armature winding had a pitch differing from $\frac{2}{3}$ and the field was of the laminated cylindrical type. In several tests the temperature rise of the rotor winding was about 100 per cent, and of the armature winding about 20 per cent, greater than that obtained under full load conditions. A solid cylindrical field would doubtless cause still greater temperature rises.

C. J. Fechheimer (communicated after adjournment): The zero power factor method of making heat runs on alternating-current generators is in general the most desirable one, provided the necessary equipment is available. Although this method may give slightly pessimistic results in regard to temperature, especially that of the field coils, it should be remembered that it is difficult to predict the power factor of a system. The effect of lagging currents of lightly loaded induction motors upon reducing the power factor is seldom appreciated. Even though generators be sold for 80 per cent power factor, it is well to give the customer the benefit of every doubt and test his machines at zero power factor. If desirable, we can easily determine what the rotor temperature will be, by taking this to vary as the square of the field currents.

When it is impossible to test synchronous machines at zero power factor, compromise heat runs should be made instead.

Among these is the direct-current open delta heat run, which gives results closely approximating those which would obtain in regard to stator temperature when the corresponding load is applied. With this method the losses in the pole shoes with attendant rise in temperature are not nearly so serious a matter as might appear at first thought, as the magnetomotive force required for the air gap is generally so great that the ampere-turns produced by the current in the delta are correspondingly small. It is often possible and desirable to use a multiple-circuit winding or equivalent, and cause direct current to flow so as to have currents in opposite directions in the same slot, provided the familiar two, layer winding is employed. We would call attention to Mr. Sebastian Senstius's paper entitled *Heat Tests on Alternators*, presented to the Institute in 1906*. We believe it adviable for the Standards Committee to consider methods of making heat runs as described by Mr. Senstius as substitutes for the more desirable zero power factor method. It is our opinion that when making such direct-current heat runs, the excitation should correspond to open-circuit voltage equal to the vector sum of the impedance drop and the terminal voltage. The current could be increased to allow for eddy currents if deep conductors are used, as described by Mr. A.B. Field.** This would then give an equivalent of full-load core loss and circulating currents equivalent to full-load copper loss. It is generally advisable to have an open-circuit heat run in addition, from which latter the field heating at any field current can be determined with considerable accuracy, as a fresh supply of air comes into the rotor (which we are assuming to be the field) and hence the temperature of the fields will not be affected by the stator temperature. The latter is undoubtedly affected by the rotor temperature, as a hot rotor causes warm air to be thrown on the stator. For two-phase machines, we could usually employ multi-circuit arrangements as described by Mr. Senstius.

When the above methods are unwieldy, we may resort to the familiar open- and short-circuit heat runs. We do not favor alternate open- and short-circuit runs of short duration. It is frequently difficult, especially on large machines, to which this method should be particularly applicable, to make such changes rapidly, and unless they are made rapidly the method is hardly desirable. Furthermore, the time of application and the magnitude of the voltages and currents are subject to calculations, such calculations being based to some extent on assumptions, and hence we are liable to be misled as to the proper substitute for true full-load conditions.

For a number of years we have endeavored to establish some relation between the sum of the open-circuit and short-circuit temperature rises and the corresponding load temperature

*TRANS. A. I. E. E., Vol. XXV, p. 311.

***Eddy Currents in Large Slot-Wound Conductors*, TRANSACTIONS A. I. E. E., 1905, Vol. XXIV, p. 761.

rise. In order for the Standards Committee to decide what ruling to give when open- and short-circuit heat runs are made, they should have available many tests for comparison. There are, to be sure, many variables that come in, yet we believe it is possible to give an approximate ruling which may be applied in absence of methods for making more accurate tests.

We shall not take space to show why the load temperature rise should be slightly less than the sum of open- and short-circuit temperature rises. This amount to be deducted we have found to be approximately 5 deg. cent. when the sum is 40 deg. and in general is proportional to the sum. The temperature reading to be taken in short-circuit and open-circuit runs, as well as the load heat run, should be the maximum that any of the several thermometers record, whether they be placed on stator coils or stator iron.

In order to determine the internal voltage we add vectorially the impedance drop to the terminal voltage. The reactance can be measured with the rotor removed and normal current circulated at normal frequency in one phase of the winding; for example, if the machine be star-connected three-phase, the current should be circulated between neutral and terminal. This may not be in entire agreement with statements which others have made, but we have found, to substantiate our statement, that such methods when used for the reactance drop in determining the zero power factor curve give extremely close results.

In regard to heat runs on induction motors when the equipment for making the load tests is not available, the "reversed rotation method" frequently gives accurate results, but we believe this is due to a number of errors cancelling each other by chance, and it should generally not be relied upon. It is well known that the frequency of the currents in the rotor circuit when the motor is operated at 200 per cent slip is double the stator frequency and hence the eddy current loss may be considerable. Therefore the results are liable to be misleading. The method, in our opinion, may be used in combination with the no-load heat run, if the depth of the rotor conductor is not greater than 0.55 in. (13.97 mm.) for 25 cycles, nor more than 0.35 in. (8.89 mm.) for 60-cycle motors. Our experience indicates that erroneous results are obtained if these limits are greatly exceeded.

Usually, we prefer the reduced voltage method for determining the temperature rise due to copper loss, the induction motor being operated until the temperature ceases to rise with the impressed frequency raised above normal (*i.e.*, the motor operates with positive slip as an induction motor) and then to have the test repeated with the frequency reduced a corresponding amount below normal (so that the motor operates with a negative slip as an induction generator). In both cases the motor is operated at normal speed in order that normal ventilation may be secured. The reason for operating at two frequencies is to insure an average

temperature which would be approximately the same as obtained with normal eddy current loss in the stator. The higher frequency produces too large and the lower frequency too small an eddy current loss in the stator copper. We should then allow for the temperature rise on open circuit, as Messrs. Collins and Holcombe have done, but whose equation we would modify as follows:

$$T_f = \left(T_r - T_n \frac{E_r^2}{E_n^2}\right) + \left(T_n - T_r \frac{I_n^2}{I_r^2}\right) - T_v$$

E_n = Normal voltage.
E_r = Reduced voltage.
I_n = No-load amperes.
I_r = Reduced voltage amperes.
T_f = Temperature rise on stator for full-load normal volts.
T_n = Temperature rise on stator for no-load normal volts.
T_r = Temperature rise at reduced voltage.
T_v = Temperature rise to be deducted.

"T_v" should follow the same general ruling as applies to the alternating-current generators as indicated above.

We believe it would be well to incorporate in the Standardization Rules some means of allowing for a machine feeding back heated air upon itself. For example, if the machine is placed in a testing pit the walls of the pit return to the machine the air which has been expelled, and thus cause a higher temperature rise than would be secured were the entire machine placed above the floor line. We have observed numerous tests which proved beyond doubt that if air once expelled is fed back into the machine before cooling, the temperature rise will be considerably more than if a fresh supply were fed continually.

(b) Transformers

J. M. Weed: I notice in the paper "Sources of Error in Transformer Tests" by Messrs. McConahey and Fortescue, a reference to the iron loss, as follows: "Due to the voltage drop in the primary winding, the induction in the iron will be slightly decreased in going from no-load to full-load, this tending to decrease the iron loss slightly." I infer from this that the authors of this paper are thinking of the name-plate voltage as the no-load voltage, and that the voltage will be lower than the name-plate voltage at the full-load condition. The voltage will be lower at the full-load condition than at the no-load condition, certainly, but if we consider the name-plate voltage as the no-load voltage, this gives a reduced output to our transformers on the basis of a current rating figured on the name-plate voltage.

A similar opportunity for misunderstanding, on this same point, exists in the paper on "Losses in Transformers" by Mr. Lewis, in his recommendation No. 1, which states that the no-load losses should be measured at rated voltage minus I_r,

where I equals rated current, and r equals resistance of primary circuit. Possibly Mr. Lewis does not mean name-plate voltage by rated voltage, but something higher, which includes the transformer drop, and will give the name-plate voltage on the secondary terminals at full load. This, however, would make the rated primary voltage dependent upon the power factor of the load, since the transformer drop depends upon the power factor. It would seem preferable to specify that the no-load loss should be measured at name-plate voltage plus $I\,r$, where r equals resistance of secondary circuit. The exact value of this correction would depend upon which winding is to be used as secondary (where the per cent $I\,r$ differs for the two windings) and upon the temperature of the transformer when the measurement is made. The correction will ordinarily be small, in any event, and my own recommendation would be to neglect it, unless for special exaggerated cases, measuring the no-load loss at the name-plate voltage.

I should like in connection with these papers (Group 3) to call attention to my discussion of the papers of Group 2, with reference to the opposition method of determining temperature rise.

C. Fortescue: The paragraph referred to by Mr. Weed brings up the question of whether the rated voltage shall be the no-load secondary voltage or the full-load secondary voltage. The paragraph referred to is true whether we consider the rated voltage as no-load or full-load—there is a voltage drop in the primary winding, and the effective induction, that is, the induction that links the secondary circuit, will be slightly decreased. On the other hand, at certain spots in the iron, the leakage flux will cause the induction to be higher, than even in the case of no-load conditions. That is what I refer to in that paragraph.

In connection with Mr. Madden's paper, I want to say that I agree with the points he brings up as improvements over the methods indicated in my paper on temperature measurement. It is preferable to measure the resistance of the copper at some point during the copper or short-circuit period. The middle points are not necessarily the correct points, but if the complete period is reduced to a short length of time, then the error in taking the middle point of the short-circuit period will be negligible.

J. M. Weed: I would like to emphasize the advantages of the use of the idler in determining temperature rises of transformers, which has been fully dealt with in the papers, but I doubt if the full advantages are appreciated by many here. The idler not only supplies a satisfactory base temperature or equivalent room temperature, but also affords a more accurate method of determining the temperature rise of the transformer, which is brought out in the paper by Messrs. Johannesen and Wade. In the formula which represents the calculations which must be made from the test in order to get the temperature rise of the

windings of the transformer, nothing appears except the voltmeter readings. In the determination of rise of resistance, by the ordinary voltmeter-ammeter method, it is necessary not only to get correct results from the reading of two meters, which involves the inaccuracies of calibration as well as the inaccuracies of observation, but you must know the exact temperature of the transformer at the time you are measuring this resistance cold in order to get an accurate temperature reading. That involves many chances of error, when you consider that the temperature rise depends upon the difference between two quantities, which are large with respect to this difference, which is a consideration that is not fully appreciated. In the case of the use of the idle transformer, it is not necessary to know the temperature of the transformer when the initial resistance readings are taken, provided the transformer upon which the heat run is made is at the same temperature as the idle transformer; and, again, the same current passes through both transformers, so that it is not necessary to know the exact value of the current. It is only necessary to know the voltmeter readings. At the end of the run, voltmeter readings are obtained with the same current passing through both transformers, again. In this case, in order to calculate the temperature rise, it is necessary to know the temperature of the idle transformer, but we have every opportunity to get this temperature correctly. This method, I believe, reduces the unavoidable errors in determining the temperature rise to a minimum.

There is one open question, however, as to the accuracy obtained with the idle transformer, and that is as to whether it is actually affected by change of room temperature in the same manner as the loaded transformer. In the loaded transformer we have a circulation of oil due to the load itself which causes all parts of the oil to come in contact with the tank within a short period of time, whereas in the idle transformer the circulation is very sluggish. If the room is warmer than the oil, the oil coming in contact with the tank will rise slowly to the top and stand in a layer, which will gradually increase in thickness. Vice versa, if the room is cooler, the oil in contact with the tank will gradually fall and produce a cool layer in the bottom of the tank, which will gradually build up from the bottom. The average temperature of the oil may not be the average between the top oil and the bottom oil, but depends upon the distribution of temperature within the tank from top to bottom.

M. G. Lloyd (communicated after adjournment): While considering the subject of transformers I want to suggest that a definition of the term "ratio of a transformer" should be included in the Standardization Rules. Heretofore this expression has been used in a variety of senses, not only in a casual way but in printed treatises upon the subject. In looking over the literature one finds that many authors fail to define this term and others use it without any exact significance. The principal

meanings attributed to the expression are as follows, in the case of a potential transformer:

1. The ratio of the number of turns in the primary winding to the number of turns in the secondary winding.
2. The ratio of the number of secondary to the number of primary turns.
3. The ratio of the terminal voltages.
4. The ratio of terminal voltages under no-load.
5. The ratio of the induced voltages in the two windings. On account of leakage, this is not the same as the ratio of turns.

No word should be used by technical men which has not a definite meaning, and in view of the great divergence in the usage of this term it seems very desirable that a definition should be included in the rules. This definition should be one which will make the term most useful to the engineer, and unless there is some good reason for departing from the most common practise among those who have occasion to use the term most frequently in an exact sense, this practise should be standardized.

Probably the reason for the previous laxity in definiteness of meaning has been the fact that the expression "ratio" has been largely used in a qualitative sense, and naturally the ratio of turns expresses such a value. With the advent of the instrument transformer, occasion arose for the use of exact quantitative values of the ratios of terminal voltages in the potential transformer and of currents in the series transformer. The time has therefore arrived, indeed it has passed, when a quantitative definition should be standardized.

In connection with this definition there are two principal considerations. One is as to whether the ratio of the primary value to the secondary value shall be used or the ratio of the secondary to the primary. General usage as well as general opinion seems to favor using the ratio of the primary quantity to the secondary quantity, whether this be the number of turns or the electrical magnitude. I will consequently not elucidate the arguments on this point.

The second principal question to be decided is as to whether the ratio of turns or the ratio of electrical magnitudes shall be meant when the word "ratio" is used. Owing to internal resistance and to magnetic leakage, the ratio of terminal voltages in a potential transformer is never quite the same as the ratio of turns. In consequence of this it is customary for the manufacturer to slightly alter one of the windings from the number necessary to give the nominal ratio of turns. The ratio of turns is not indicated on the name-plate and is usually unknown to the user. The name-plate should always, and usually does, tell the ratio of the terminal voltages under some definite condition of use, for this is the ratio of interest to the user. A similar condition exists with regard to series transformers. Here again the ratio of turns is not the value which is of interest and importance to the user, and it is not customary for the manufacturer to

state on the name-plate this ratio, but rather the ratio of primary to secondary currents under some definite condition of use.

In the case of the constant-current transformer used with primary on a constant-potential circuit, the ratios of potentials and of currents are of little interest and their values need not be known to the user.

Should the ratio represent a quantity which is fixed by the number of conductors or a quantity which varies with the conditions of use? Should it represent a quantity whose value is secreted in the archives of the manufacturer, or a quantity whose value can be determined by a simple measurement? Should it represent a quantity whose exact value is of importance to the user or a quantity which it is only useful to know approximately?

Inquiry among the men who have occasion to make use of exact quantitative values of ratio discloses a universal preference for defining the term "ratio" to mean the ratio of the primary electrical magnitude to the secondary electrical magnitude. The only point which may really seem to be at issue is as to whether this ratio should be defined as a definite constant quantity for a particular transformer, or whether it should represent a magnitude which may be changed under the conditions of use. For instance, in the case of a potential transformer, shall the ratio mean the quotient of terminal voltages under particular conditions of frequency, secondary load, etc., or shall it be regarded as varying when these and other conditions of use are varied? The question is somewhat similar to that involved in making a distinction between the rating of an electrical machine and its capacity. The capacity is a quantity which varies with the conditions of use, such as room temperature, power factor, etc., but the rating may be so defined as to be a definite quantity for a particular machine, independent of any temporary conditions under which it may be used. To me it seems preferable to regard ratio as a variable quantity, and I therefore suggest the following definitions:

"The ratio of a potential transformer is the ratio of the effective primary terminal voltage to the effective secondary terminal voltage."

"The ratio of a current transformer is the ratio of the effective primary current to the effective secondary current."

It is to be noted that with the above definition the regulation of a potential transformer is the change in ratio between full load and no load, expressed as a fraction of the ratio at no load.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

RATING OF OIL CIRCUIT BREAKERS WITH REFERENCE TO RUPTURING CAPACITY

BY GEORGE A. BURNHAM

There are several ways of rating the rupturing capacity of oil circuit breakers in use at the present time, and when comparing this class of apparatus of different manufacturers considerable explanation and detail are involved. For example, one company will rate the circuit breaker in "ultimate rupturing capacity;" another will specify that the circuit breaker is suitable for use on a circuit of certain characteristics or base the rupturing capacity on the aggregate full-load capacity of all synchronous apparatus.

The rating of oil circuit breakers with reference to rupturing capacity is an important matter and deserves the careful consideration of the Standards Committee.

The purchaser or user of this class of apparatus is interested in how much energy or kilovolt-amperes a particular circuit breaker will safely interrupt. The answer at the best is only an estimate based on familiarity with design, tests and actual service. I believe that most engineers and designers will agree that the proper selection of a circuit breaker with reference to rupturing capacity depends as much on the characteristics of generator, transmission line and translating devices as on the design of the circuit breaker itself. The designer has fixed the characteristic of the circuit breaker, but, on the other hand, has no control over the characteristic of the distribution system, and the characteristics are vastly different in transmission systems of the same kilovolt-ampere capacity.

Rating circuit breakers with reference to the aggregate full-load rating of all synchronous apparatus alone is not sufficient

to guide in the selecting of the proper circuit breaker, as the location of the switching equipment, the interposed lines and apparatus are of equal importance.

It appears to the writer that the most definite and clear way of rating oil circuit breakers is to give the maximum "instantaneous" rupturing capacity, meaning by "instantaneous" the elimination of time-limit relays in tripping. This gives the engineer something definite, and one can then judge whether or not the circuit breaker is suited for the particular requirements; and the engineer of the distribution system or central station is in a better position to judge, as a general rule, than the designer, unless many details involving the characteristics of the system are first considered.

If rupturing capacity were rated as "maximum instantaneous" this would eliminate all ratings in reference to non-automatic, cell-mounted, pipe-frame mounting, time-limit tripping, limitations as to reactance, etc., and be confined entirely to the switch itself, which after all is the important factor.

It is fairly well settled that, other things being equal, the rupturing capacity of an oil circuit breaker depends on the head of oil over the break at the starting of the arc, the amount of space above the oil for gas expansion, the shape and strength of the oil tank and its fastenings, and, to some extent, the length and rapidity of contact movement.

An automatic circuit breaker with its tripping features removed becomes a non-automatic circuit breaker, but has its rupturing capacity been altered? Does the application of the time-limit relay or cell construction actually increase the rupturing capacity, or does the introduction of reactance affect the circuit breaker itself? I think most engineers will agree that these factors do not actually affect the rupturing capacity of the switch but change only the character or value of the short-circuit current and at the instant of break tend to limit the kilovolt-amperes of the circuit to that of the circuit breaker or switch controlling it.

In view of these conditions, I would suggest for the consideration of the Standards Committee that all oil circuit-breaking devices be rated with reference to rupturing capacity on their "instantaneous action."

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

THE SPHERE SPARK GAP

BY S. W. FARNSWORTH AND C. L. FORTESCUE

For many years the spark gap method of measuring high voltages has been universally used. No indicating meter satisfactory for commercial uses has yet been developed which will measure the maximum voltage as will the spark gap. Numerous investigators have made calibration curves for the spark gap using needle point electrodes under widely varying conditions. The results obtained under like conditions have checked fairly well over a range of voltage up to about 100,000. Above this voltage it has been very hard to duplicate conditions near enough for different investigators to obtain results which are in agreement.

Since voltages of 100,000 and above have come into use, requiring test voltages of 200,000 and above, the need for some more reliable means of measuring the voltage has been strongly felt. While investigating the dielectric strength of air the authors had occasion to use a sphere gap and were so favorably impressed by the consistent results obtained that the idea soon presented itself of using such a gap to replace the needle point gap.

Those who are daily handling high voltages know well the inconsistency of the needle point gap and others should be convinced of it by the great number of different empirical equations derived by different investigators showing relation between distance of separation and breakdown voltage. Besides giving inconsistent results the needle point spark gap is cumbersome and requires a great deal of space. Section 245 of the A. I. E. E. Standardization Rules specifies the following:

"The spark points should consist of new sewing needles supported axially at the ends of linear conductors which are at least

twice the length of the gap. There should be no extraneous body near the gap within a radius of twice its length." For 300,000 volts, the highest voltage given in the A. I. E. E. table, the sparking distance between needle points is 77.4 cm. (30.50 in.). If constructed according to the rule given above, the structure will have the dimensions given in Fig. 1. It is seen that a space 6.19 meters (20.33 ft.) long by 2.9 meters (11.83 ft.) wide and high is required. Three-hundred thousand volts is by no means the highest voltage manufacturers are being called upon to measure, and with increased voltage the problem becomes more difficult to solve satisfactorily. Compare the space required for the needle point gap with the space of 1.22 meters by 1.52 meters by 2.42 meters high required for a 37.5-cm. sphere gap having one end grounded and having a range of 412,500 volts, effective value. Fig. 2 gives the dimensions of such a gap as constructed and used.

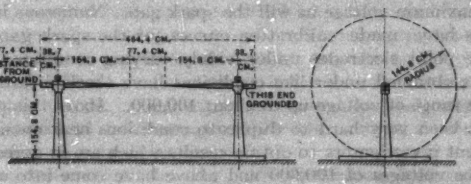


FIG. 1

A sphere gap becomes inconsistent as soon as corona forms preceding break-down voltage. This only happens when the spheres are separated a distance greater than their diameter. When separated less than their diameter a progressive break-down follows immediately upon the break-down of the film of air at the surface of the sphere.* Consequently a pair of spheres should only be used for measuring voltages up to that necessary to break down the air between them when separated a distance approximately equal to their diameter. With one end grounded, 25-cm., 37.5-cm. and 50-cm. spheres have ranges from 50,000 up to approximately 275,000, 412,500, and 550,000 volts, effective values, respectively. Other sizes have ranges in proportion.

*Alexander Russell and others have given mathematical proof as to why this is so. See "The Dielectric Strength of Air." *The Philosophical Magazine and Journal of Science*, Volume 11, Sixth Series, page 237.

With middle point grounded, 25-cm., 37.5-cm. and 50-cm. spheres have ranges up to approximately 330,000, 440,000 and 650,000 volts, respectively. Other sizes have ranges in proportion.

Fig. 2 gives the dimensions for the 25-cm., 37.5-cm., and 50-cm. gaps. Being constructed vertically, they use a very small floor space as compared with equivalent horizontal needle point gaps. The top sphere is stationary but slightly adjustable in height so as to just make contact with the lower sphere when it is set for zero separation. The lower sphere is mounted on a piece of brass tubing which carries a threaded bushing on its lower end. This bushing works on a carefully threaded rod having a pitch of two per centimeter. The bushing being graduated to fiftieths on its circumference, separation may be measured to the nearest 1/100 cm.

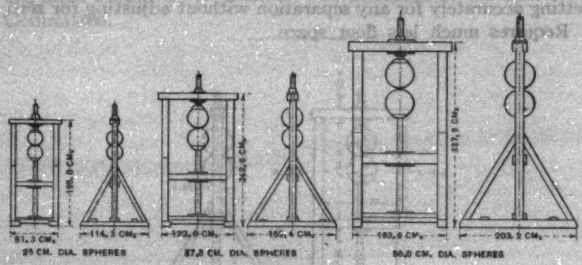


FIG. 2

directly. Thus, there is a micrometer adjustment provided. Being made of large parts, the whole arrangement is mechanically strong and the spheres are kept in constant alignment. Being mounted on large wheels the spark gap sets are very portable and may also be picked up by a crane without risk of damage.

The first pair of spheres 25.4 cm. (10 in.) diameter were made up early in 1910 and immediately became so popular on the testing floor because of their consistency and convenience that the use of the needle point gap was entirely abandoned. These original spheres are still in use and show no sign of surface deterioration due to the arc. Various resistances have been used in series with the gap to limit the current upon break-down. A value of one ohm per volt for the maximum voltage for which the set is to be used has been found to give entire satisfaction and the

resistance may be of any convenient form. The proximity of neighboring bodies has been found to have little effect on the break-down voltage of a given gap. The effects of atmospheric pressure and temperature are well known, the break-down voltage varying directly as the pressure and inversely as the absolute temperature. Humidity has a negligible effect.

The sphere gap thus offers a means of measuring high voltages which has the following advantages over the needle point gap:

More consistent, the break-down voltage varying directly a the pressure and inversely as the absolute temperature and being affected only to a negligible degree by humidity, proximity to neighboring bodies, frequency, etc.

More convenient, because the terminals do not have to be renewed, and a micrometer adjustment provides ready means of setting accurately for any separation without adjusting for zero.

Requires much less floor space.

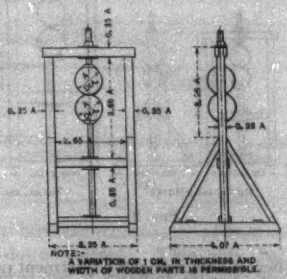


FIG. 3

Is more portable because of its better mechanical construction and smaller size.

In view of the above advantages which have been found to exist during nearly three years' use in commercial testing, the authors feel that the sphere spark gap may be well considered as a standard to replace the needle gap standard.

It is suggested that the following features be incorporated in the Standardization Rules covering the measurement of high voltages:

1. Either one end or the middle point of the high-tension winding should be grounded. In case the middle point is grounded,

the high-tension voltage from one terminal to ground may be measured by the spark gap, and total voltage taken as twice this value.

2. The spark gap shall consist of two accurately machined spheres supported vertically by a wooden frame-work having its dimensions proportional to the diameter of the sphere used, as shown in Fig. 3.

3. The 25-cm., 37.5-cm. and 50-cm. spheres shall be standard sizes covering voltage ranges of 50,000 to 275,000, 50,000 to 412,500 and 50,000 to 550,000 volts, effective values, respectively. The lower sphere shall always be grounded.

For voltages below 50,000 a smaller size of sphere may be used. The authors are not at present in a position to recommend a definite size. It is suggested that the calibration of the standard sizes should be done under the direction of the Standards Committee.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

CALIBRATION OF THE SPHERE GAP VOLTMETER

L. W. CHUBB AND C. FORTESCUE

The breakdown strength of air between spherical terminals has been found to be rather constant, and the sphere gap has been suggested as a standard instrument to be used in the measurement of high voltage. Results obtained with different apparatus by different experiments, however, have not been in perfect accord, and the ultimate dielectric strength of air indicated by calculating the maximum intensity from these tests, has shown some calibrations of the gaps to disagree with results obtained by other methods.

If spheres of sufficient size are used, and if the separation and breakdown voltage are such that there is no corona at the surface of the spheres, it is fair to assume that the complete breakdown of the air gap will occur at the voltage at which the stress due to the intensity at the surface of the spheres corresponds to the ultimate strength of the air. It also seems as though the rupture of a given sphere gap should be independent of frequency of time of voltage application, and that it should depend only upon the maximum value of the voltage impressed, provided that there is no ionization before breakdown which in effect alters the shape of the terminals and changes the dielectric gap.

The purpose of this paper is to present the calibration curves for the three sizes of sphere gaps which have been suggested as standards.*

To be of value in measuring voltage, the sphere gap must be furnished with a calibration curve showing the relation between the breakdown voltage and length of gap. The results of any

*See paper by Farnsworth and Fortescue, p. 733 of this volume.

calibration can be no better than the method used in the test, and unless such calibration is accurate the sphere gap voltmeter is not a desirable standard.

Different methods used to calibrate spark gaps at high voltage show great variations in the relation between voltage and separation of spheres. Some also show a great variation with frequency. It can be shown that such differences are due to conditions of test rather than to any real variation of the sphere gaps themselves.

The most usual method of measuring the high-tension voltage is to measure the primary potential and multiply by the ratio of the transformer. Voltages obtained by this method are generally very much in error, due to the distributed capacity in the high-tension winding of the transformer, harmonic distortions of the applied voltage wave, and the capacity of the terminal bushings and the apparatus to which the high-voltage winding is connected. The effective, or r.m.s., low-tension voltage is usually indicated so that there is no measure of the maximum unless a pure sine wave of voltage is applied, there are no appreciable distortions due to the harmonic components of the exciting currents, and the capacity regulation can be corrected.

The use of a second high-voltage transformer to step down the voltage for measurement with a voltmeter, is an improvement over the straight ratio method, but requires corrections in most cases, and another expensive transformer.

Another method of measuring the high voltage which has been used by the authors is to connect an electrostatic voltmeter of low electrostatic capacity in parallel with one or several sections (at the ground side) of a condenser type terminal. This method corrects the reactive errors of the ratio method but is also an effective reading and gives no indication of wave shape and maximum value.

The calibration of the sphere gaps was thought to be dependent only on the maximum voltage and it was the aim of the authors to obtain the calibrations in terms of maximum of the voltage of the high-tension winding, and then reduce the results to effective values, assuming sine wave shape of voltage.

A very satisfactory method of measuring the maximum of the voltage wave was to rectify the capacity current taken by an air condenser and measure the average value of the rectified current with a d'Arsonval galvanometer. The details of this method will probably be of interest.

Fig. 1 shows diagrammatically the apparatus and circuits necessary to calibrate the gap in terms of the maximum voltage.

The air condenser is shown in Fig. 2. It was constructed of wood carefully turned to dimensions and coated with tin-foil and lead sheeting. The central and high-voltage member was 60 cm. (23.6 in.) in diameter and 458 cm. (15 ft.) long. The outside or ground member with the flared ends had a total length of 240 cm. and internal diameter of 162.8 cm. (5.34 ft.) It was divided into three sections; the middle or working part was 47.7 cm. (18.8 in.) long and the end sections or guard rings were each of equal length in the cylindrical part and were flared with toroidal surfaces having a radius of 47.7 cm. (18.8 in.). The capacity of the central section was figured and found to be $2.657 + 10^{-11}$ farad.

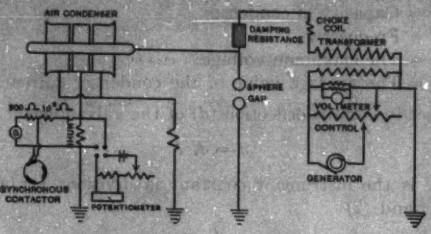


FIG. 1

The central section of the outside member was connected to ground through a non-inductive resistance which served as a shunt to measure its charging current. The guard ring sections were connected together and grounded through a resistance of such a value that the time constants of the center and ends would be approximately the same, and there would be no cause for leakage between the three sections. Across the resistance between ground and the central section, was connected the galvanometer circuit consisting of a megohm of series resistance and a d'Arsonval galvanometer shunted with a synchronous contactor. The contactor was driven by a six-pole synchronous motor and arranged with three equal brass segments which short-circuited two brushes during every alternate half cycle. The brushes were connected to a long lever so that they could be readily shifted in phase. A maximum deflection of the galvanometer in this

case indicates commutation at the zero points of the current wave, and this maximum deflection was proportional to the average charging current of the condenser section and also proportional to the maximum voltage impressed upon the condenser.

If Q is the quantity required to charge the condenser to any maximum potential V, the passage of $2Q$ is required to change the potential from $+V$ to $-V$ for the symmetrical periodic charge. While the potential changes from $-V$ to $+V$, the reversal of current is suppressed in the instrument by the shunting effect of the synchronous contactor. The steady deflection of the instrument is therefore caused by a unidirectional pulsating current. The average value of the condenser current (disregarding sign) is equal to the quantity flowing, in coulombs per second.

$$I = 4\,Qf = 4\,C\,Vf \tag{1}$$

where C = Capacity of condenser.
f = Frequency.
V = The maximum voltage.
and I = The average value of the condenser current.

The steady current deflection (d) of the galvanometer is

$$d = K\,I \tag{2}$$

where K is the instrument constant in divisions per ampere. From (1) and (2)

$$V = \frac{d}{4\,C\,K\,f}$$

In all cases the value of K was obtained by applying the battery voltage to the galvanometer circuit while the contactor was running.

In order to make sure that the contactor was making good contact at all times, frequent check tests were made with the contactor running, and still to make sure that currents for equal deflections were in the ratio of 2 to 1. The galvanometer was critically damped so as to obtain quicker readings, and to eliminate errors due to overshooting and swinging which would occur with voltage variations and phase shifts. With the instrument under-damped it was difficult to distinguish between voltage variations and false setting of the brushes. When over-damped the proper position of the brushes for the maximum reading could readily be found, when the voltage was steady, but the response to quick changes in voltage was not sufficient, and it

FIG. 2. [CHUBB AND FORTESCUE]

T—Transformer; C T—Condenser terminals; C C—Choke coil; R—Resistance; S S—Sphere gap; A C—Air condenser; G—Galvanometer.

was impossible to tell whether the breakdown of the gap was due to a surge of voltage or not. Throughout the work, all wiring, instruments, switches, resistances in the circuit, and the contactor were shielded with grounded coverings of tin-foil or wire screen in order to remove static troubles. Serious errors were introduced when any part of circuit was left unshielded, but the strong static field had no bad effects when the shields were properly grounded. There was an appreciable capacity between the high-tension terminal and the ground side of the condenser, and in order to prevent errors due to this additional condenser current, through the measuring shunt, it was necessary to place a grounded network of wires between the condenser and the high-potential circuits. Before each test a high voltage was applied, with the condenser disconnected and short-circuited, to find out if there were any static or electromagnetic troubles which would give a deflection of the galvanometer. If no such troubles were present the high-tension lead was connected to the condenser and tests made as follows:

The gap was opened two or three cm. beyond the breaking point. Voltage was then applied to the condenser and gap. After the maximum deflections of the galvanometer had been carefully observed, the sphere gap was very slowly closed until breakdown occurred. The maximum value of the voltage was then worked out from the galvanometer readings and a direct-current calibration made after each test. The relation between this maximum voltage and the separation of the spheres was then plotted.

In the later tests the contactor was driven with a 30-h.p. induction motor instead of a synchronous motor. By making this change both positive and negative maxima could be observed, and no shifting of brushes was necessary, as the adjustment for maximum deflection was obtained each time the rotor of the motor had slipped a pole pitch. At 60 cycles, the motor slipped less than one revolution (6 poles) per minute, so that with the critically damped galvanometer, accurate observations of the two maxima could readily be made. At lower frequency the per cent slip was of course greater, but the frequency of galvanometer maxima was about the same.

Tests were made at frequencies ranging from 25 to 60 cycles with two high-voltage transformers, each excited from two different sources of power.

The authors hoped to calibrate the 37½-cm. and 50-cm. spheres to 500 kv. (effective) on a third and larger transformer, but lack

of time and a great volume of commercial testing delayed these tests.

It was assumed that a good test on the 25-cm. spheres up to the voltage corresponding to a diameter separation could be made on the 300-kv. transformer and the calibrations of the larger gaps obtained by extrapolation and the theory of proportional fields.

If the calibration of the 25-cm. spheres showed a constant surface intensity throughout, and if the larger set agreed within the same range of voltage, such an extrapolation could not be

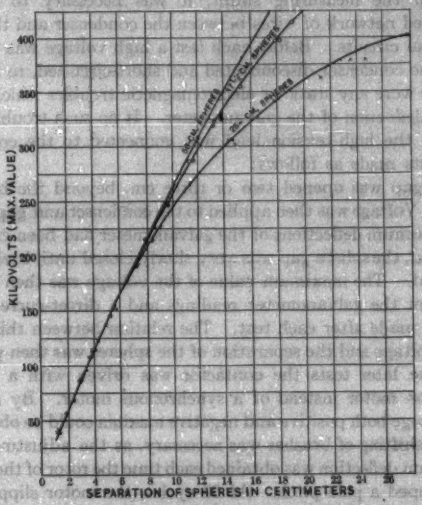


FIG. 3

questioned. The results, however, show increasing intensity with an increase in separation, and show the air between the larger spheres to be apparently weaker than between the small spheres for the same ratio of separation.

The increase of surface intensity with increase in separation has been observed by several experimenters, but not satisfactorily explained. The relative weakness of the air gaps between the large spheres is probably due to the effect of neighboring bodies.

Extraneous objects at constant distances from the gaps will of course weaken the gap between the larger spheres more than that between the smaller spheres. Quantitative tests of the effect of extraneous objects will be made later.

The results of the tests show frequency and wave shape to have no appreciable effect upon the calibration.

TABLE I
25-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-3}$	V kv.	Remarks Test No. 36
32	37	69	24.8	25	1.31	658	39.6	
32.5	36.5	69	24.8	"	1.19	"	39.6	
76.5	82	158.5	58.5	"	3.10	"	90.9	
76.5	82.5	159	58.5	"	3.10	"	90.9	
96.6	102.5	199.1	75	"	3.86	"	114	
97	102.3	199.3	75	"	4.07	"	114.3	
98.5	102.2	200.7	75	"	4.06	"	115.1	
131.5	135.5	267	100	"	5.52	"	152.8	
131.5	137	268.5	100	"	5.56	"	154	
118.5	122	240.5	90	"	4.92	"	137.8	Damping not good
106	108.5	214.2	80	"	4.38	"	122.6	brush tightened
92.5	94.5	187	70	"	3.79	"	107.2	
92.5	94	186.5	70	"	3.76	"	106.8	
60.5	60	120.5	47.3	"	2.34	"	69	
49.2	49.6	98.8	34.6	"	1.82	"	57	
								Test No. 38
42	45.5	87.5	100	25	5.71	218	151	
42.5	45.5	87.5	100	"	5.68	"	151	
53.5	57.5	111	125	"	7.29	"	191	
54	57.5	111.5	125	"	7.32	"	192	
63.5	68.5	132	150	"	9.02	"	227	
63.3	68.8	132.1	150	"	9.08	"	227	
74	79.6	153.6	176	"	11.37	"	265	
75	80	155	175	"	11.36	"	268	
85	92.5	177.5	200	"	11.17	"	306	
85	92.5	177.5	202	"	14.67	"	306	
85.5	92.5	178	200	"	14.43	"	307	
95.3	103.5	198.8	225	"	17.80	"	343	
96.2	103.6	199.8	225	"	18.02	"	345	
106.2	114	220.3	251	"	23.56	"	381	
106.2	114	220.2	251	"	24.73	"	381	Surge of voltage
106.2	113.6	219.8	249	"	23.55	"	380	
112.5	121.5	234	264	"	27.85	"	404	
102	110.5	212.5	240	25.2	21.28	"	363	
112	121	233	260	25	27.55	"	402	
105.5	115	220.5	250	"	22.79	"	381	
84.5	93	177.5	200	"	14.88	"	303	
62.3	70.1	132.4	150	25.2	9.20	"	225	
41.5	49	90.5	100	"	5.56	"	154	
41.2	49.5	90.7	100	"	5.66	"	155	

TABLE II

37½-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-6}$	V kv.	Remarks
								Test No. 40
25	25.2	50.4	50	25	3.04	214	87.5	
24.6	25.3	49.9	50	"	2.98	"	86.4	
41.4	41.7	83.1	100	"	5.26	"	144.1	
41.5	42.5	84	100	"	5.24	"	145.6	
61	62	123	150	"	7.96	"	215.5	
60.3	62.4	122.7	150	"	8.44	"	214.8	
70.8	73	143.8	176	"	9.61	"	249.2	
70.2	72.5	142.7	175	"	9.70	"	247.5	
81.6	83.8	165.4	201	"	11.38	"	287	
81.8	84.3	166.1	202	"	11.69	"	288	Quick rise of voltage
81.2	84	165.2	201	"	11.99	"	286.6	
91.8	95	186.8	225	"	13.35	"	323.7	
91.6	94	185.6	225	"	13.27	"	321.7	
101.5	104	205.5	250	"	15.40	"	356.3	
101	104.3	205.3	250	"	15.29	"	356	
112.5	116.5	229	275	"	18.12	"	398	
112.5	116.5	229	274	"	17.88	"	398	
118	121	239	286	"	19.18	"	415	
41.2	42.5	83.7	100	"	5.27	"	145.2	

TABLE III

50-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-3}$	V kv.	Remarks
								Test No. 45
28.1	26.3	54.4	61	24.75	3.45	214	96.5	
28.1	26.2	54.3	60	25	3.38	"	95	
45.3	43.6	88.9	100	25	5.68	"	155	
45.3	43.7	89	100	25	5.68	"	156	
66	64.1	130.1	150	25.25	8.66	"	226	
65.8	65.2	131	150	24.75	8.66	"	231	
88.6	88	176.6	200	25	12.23	"	308	
88.8	88.1	176.9	201	25	11.99	"	309	Frequency unsteady
88.7	88	176.7	201	25	12.17	"	308	
99.4	99	198.4	225	25.25	13.88	"	344	
99.7	99	198.7	225	25.25	13.80	"	344	
109.4	109	218.4	249	25.25	15.43	"	378	
108.8	109.2	218	249	25	15.32	"	381	Guard ring discharges through shunt
87	89.2	176.2	202	25.25	12.20	"	303	

Fig. 3 shows the calibration curves obtained for each of the three sets of spheres and Tables I, II and III show the results for

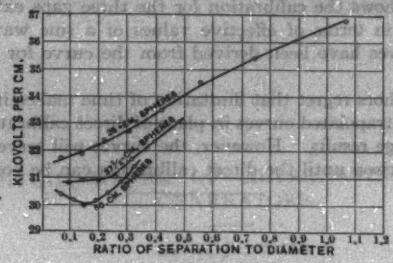


FIG. 4

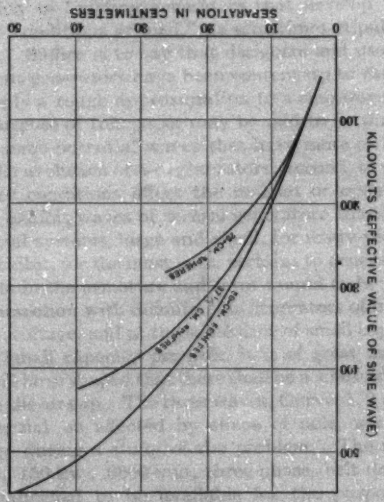


FIG. 5

a 25-cycle test of each. The curves have been drawn weighing the points of many tests. To avoid confusion, only the points of the tests shown in the tables are plotted.

Fig. 4 shows the relation between surface density and the ratio of separation for the three curves of Fig. 3.

Fig. 5 shows the calibration for the three gaps extended and expressed in terms of effective values of a sine wave voltage. These curves have been derived from the curve for the 25-cm. sphere.

The authors regret that limitation of time makes it necessary to show extrapolated curves in place of direct calibration for the high-voltage results. However, the curves will serve as a basis for comparison until the direct calibration can be completed.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

POTENTIAL WAVES OF ALTERNATING-CURRENT GENERATORS

BY W. J. FOSTER

It is not the purpose of this paper to discuss pro and con the advisability of building generators that develop "a sine wave under all conditions of load," as sometimes stipulated in specifications. Suffice it to say that designers and users of alternaing-current generators have been content up to the present time with simply a rough approximation to a sine wave.

The purpose of this paper may be said to be three-fold; first, to show some potential waves that have more or less close relation to the evolution of a-c. generators; second, to show how load and other conditions affect the no-load or open-circuit wave; third, to exhibit waves of several generators that have supplied commercial systems, large and small, for many years.

The exhibit, for the most part, pertains to generators that have open slots in the armature and form-wound coils.

In connection with definite pole generators of high periodicity and high voltage, and at the same time of small capacity, or more exactly, small capacity per pole, it is of great importance that poles shall be so shaped that there shall be a sinusoidal distribution of flux in the air gap. The three waves, Curves 1, 2 and 3, showing the potential as affected by shape of pole, were taken many years ago during a study of the problem. The machine was a 60-cycle, 150-kw., 6600-volt, three-phase, belt-driven generator which happened to be available for the purpose. The only changes made were on the pole faces. It is probable that a better wave could have been obtained by an additional trial.

Curves 4 and 5 show what was accomplished on another alternator by a slight change in the curvature of the pole face,

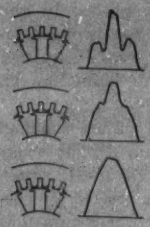
viz., a reduction from 8¼ in. (21 cm.) to 7¾ in. (19.6 cm.), of the radius to which poles were turned.

Assuming a pole of proper shape, the fundamental of the potential wave becomes a sine. The problem is then to reduce the harmonics to a minimum. Curves 6, 7 and 8 give typical curves of one slot, two slots and three slots, respectively, per phase per pole for star-connected, three-phase, high-voltage generators. These plainly show harmonics that are caused by the slots in armature. The harmonics due directly to the slots are never lower than of the fifth order in commercial generators, since there are three slots per pole in a one slot per pole per phase, three-phase machine. It is the third harmonic, more especially, that needs to be reckoned with in laying out armature windings. If the wave across each phase itself were a perfect sine with no harmonics, the wave from terminal to neutral in star-connected would be identical with that across terminals, and also with the delta-connected. Few commercial machines approximate this ideal condition.

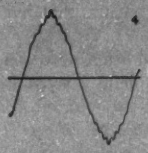
Curve 9 is an example of a poor wave, due largely to the circulating third harmonic current in the closed delta. Curve 10 is taken across the delta when opened at one corner. The wave would be poor on this generator if star-connected. Curve 11 may be taken as representative of a large number of delta-connected commercial generators which have quite good waves when star-connected. Curve 12 shows the possibilities in a delta-connected armature. This belongs to a five slot per phase per pole generator with large air gap and well shaped pole.

Sometimes in star-connected machines the wave across one phase or between terminal and neutral is broad-topped as compared with that across two phases or between terminals (see Curves 13 and 14), in other cases the converse is true.

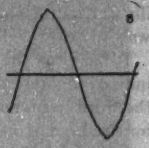
It is evident that the harmonics and, consequently, the resultant or completed wave, will be modified by varying the pitch of the armature winding or by staggering the poles, or by an irregular spacing of the poles. Equally good results have been obtained by making the number of slots in the armature not an exact multiple of the product of poles by phases—a construction much preferable to diagonalling the poles, when considered from the standpoint of mechanical design. A vernier effect is thus established between the armature and the field. This design might be designated the "hunting tooth." Curve 16



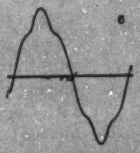
CURVES 1, 2 AND 3.—WAVE FORMS AT NO-LOAD AS AFFECTED BY SHAPE OF POLE.



CURVE 4.—POTENTIAL WAVE—NO LOAD.
18 kv-a., 25 cycles, 750 rev. per. min., three-phase, 110 volts, pole face 8½ in. radius.

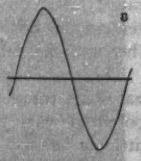


CURVE 5.—POTENTIAL WAVE—NO LOAD.
18 kv-a., 25 cycles, 750 rev. per. min., three-phase, 110 volts, pole face 7¼ in. radius.

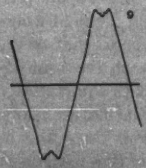


CURVE 6.—POTENTIAL WAVE—NO LOAD.
Three-phase star connected—one slot per phase per pole, 3000 kv-a., 60 cycles, 6600 volts.

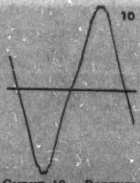
CURVE 7.—POTENTIAL WAVE—NO LOAD.
Three-phase, star connected, two slots per phase per pole, 2700 kv-a., 35 cycles, 13,200 volts.



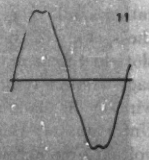
CURVE 8.—POTENTIAL WAVE—NO LOAD.
Three-phase star connected, three slots per phase per pole, 2700 kv-a., 60 cycles, 6600 volts.



CURVE 9.—POTENTIAL WAVE—NO LOAD, ACROSS TWO TERMINALS OF A DELTA CONNECTION.
4200 kv-a., 60 cycles, 720 rev. per. min., three-phase, 2300 volts.



CURVE 10.—POTENTIAL WAVE—NO LOAD, ACROSS SAME TERMINALS AS IN FIG. 9 BUT WITH OPEN DELTA.
4200 kv-a., 60 cycles, 720 rev. per. min., three-phase, 2300 volts.



CURVE 11.—POTENTIAL WAVE—NO LOAD—DELTA CONNECTED
900 kv-a., 25 cycles, 150 rev. per. min., three-phase, 400 volts.

compared with 15 shows what may be accomplished by this scheme. There is no other difference between the two generators to affect the wave except the slot ratio. Curve 17 is another illustration of the good results that have been obtained in this way.

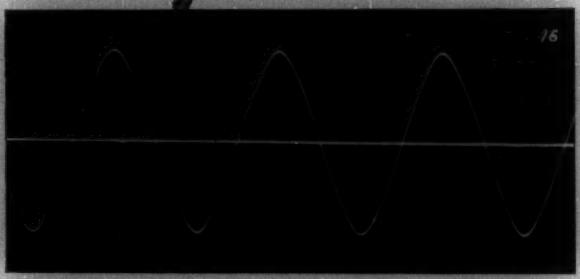
It has been the general practise to connect armature windings indiscriminately star or delta, except in certain designs where the third harmonic is too pronounced. Curves 18 and 19 superimposed, show at a glance the differences that existed in connection with one of the earlier steam-turbine generators that was standard for several years. It is sometimes advisable, when testing a delta-connected armature of a new design, to open a corner of the delta and insert an ammeter to measure the circulating current, or take an e.m.f. wave across the open corner. Curves 20 and 21 are oscillograph records of investigations made on a cylindrical rotor with distributed field winding. Incidentally, these records show the influence of the third harmonic current, when flowing in the closed delta, on the potential wave of the fundamental itself.

The star-connected generators are not immune from third harmonic trouble in case the neutrals of generators differing in potential wave are grounded without resistance, or with very little resistance. Curves 22 and 23, superimposed for easier comparison, are of 7000- and 11,000-kv-a. generators, respectively, in connection with which the current to ground was so large as to overload the armature windings and make parallel operation impossible with both neutrals direct to ground.

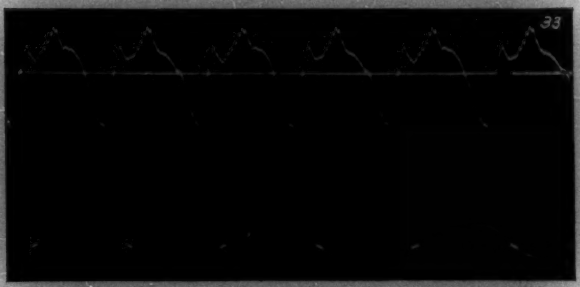
Potential waves are often modified, both under load and no-load conditions, by circulating currents in the pole faces or in amortisseur windings on the field. Curve 24 shows a wave taken on a 13,200-volt synchronous motor with broad open slots, rather small air gap and squirrel-cage winding on the field where the spacing of the bars in the poles was too close to that of the slots in the armature. Curve 25 is the wave with the squirrel-cage winding removed. Curve 26 is the wave with squirrel-cage winding in place and magnetic wedges in the armature slots. Unfortunately this wave had to be taken at about three-fourths voltage, on account of the heat generated in the wedges at voltages approaching the normal. Curves 27 and 28 are examples of good waves of synchronous motors with squirrel-cage windings.

Potential waves taken anywhere that differences of potential

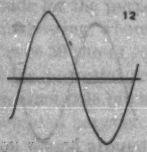
CURVE 15.—POTENTIAL WAVE, NO LOAD. [FOSTER]
150 kv-a., 60-cycles, three-phase generator, one slot per phase per pole.



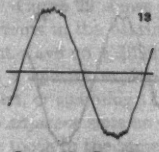
CURVE 16.—POTENTIAL WAVE NO LOAD [FOSTER]
150 kv-a., 60-cycle, three-phase generator, 1½ slots per phase per pole.



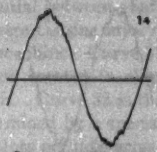
CURVE 33.—POTENTIAL WAVE ON EXPLORING COIL IN FIELD. [FOSTER]
800-kv-a., 25-cycle, 3300-volt generator carrying single-phase load.



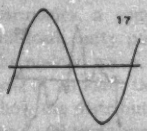
CURVE 12.—POTENTIAL WAVE—NO LOAD.
Delta connected, 6000 kv-a., 50 cycles, 250 rev. per. min., three-phase, 2300 volts, long distance transmission in system of 30,000 kw.



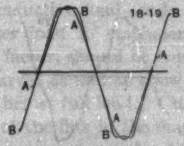
CURVE 13.—POTENTIAL WAVE—NO LOAD. ACROSS ONE PHASE.
2400 kv-a., 60 cycles, 360 rev. per. min., three-phase, 11,000 volts. (Amortisseur windings).



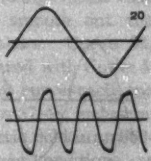
CURVE 14.—POTENTIAL WAVE—NO LOAD. ACROSS TWO PHASES.
2400 kv-a., 60 cycles, 360 rev. per. min., three-phase, 11,000 volts. (Amortisseur windings.)



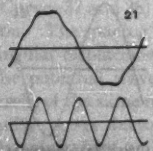
CURVE 17.—POTENTIAL WAVE—NO LOAD.
8400 kv-a., 50 cycles, three-phase, 11,000 volts, 3½ slots per phase per pole.



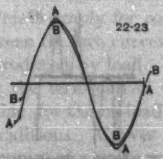
CURVES 18 AND 19.—POTENTIAL WAVES—NO LOAD
No. 18—Curve A, star connected. No. 19—Curve B, delta connected 2100 kv-a., 60-cycle, three-phase generator.



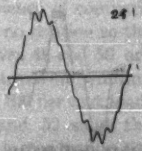
CURVE 20 — OSCILLOGRAMS—NO LOAD, OPEN DELTA.
Upper curve, potential across one phase. Lower curve, potential across open delta. 1250 kv-a., 60 cycles, 4000 volts.



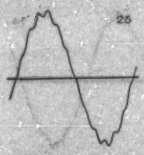
CURVE 21. — OSCILLOGRAMS—NO LOAD, CLOSED DELTA.
Upper curve, potential across one phase. Lower curve, potential across closed delta. 1250 kv-a., 60 cycles, 4000 volts.



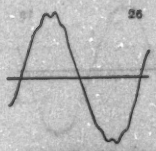
CURVES 22 AND 23.—POTENTIAL WAVES NO LOAD
Two generators with neutrals grounded, three-phase, 25 cycles, 9000 volts. A, 7000 kv-a., B, 11,000 kv-a.



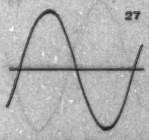
CURVE 24.—POTENTIAL WAVE—NO LOAD.
700 kv-a., 60 cycles, synchronous motor, squirrel cage windings, three-phase, 13,200 volts.



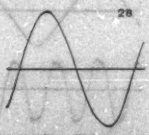
CURVE 25.—POTENTIAL WAVE, NO LOAD.
700 kv-a., 60 cycles, synchronous motor, squirrel cage removed, three-phase, 13,200 volts.



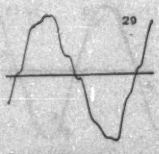
CURVE 26.—POTENTIAL WAVE, NO LOAD, AT 9500 VOLTS.
700 kv-a., 60 cycles, synchronous motor, squirrel cage winding three-phase, 13,200 volts, magnetic wedges.



CURVE 27.—POTENTIAL WAVE—NO LOAD
90 kv-a., 60 cycles, synchronous motor, with squirrel cage winding, three-phase, 220 volts.



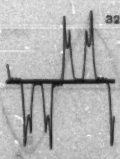
CURVE 28.—POTENTIAL WAVE — NO LOAD.
450 kv-a., 60 cycles, synchronous motor, three-phase, 480 volts, squirrel cage winding.



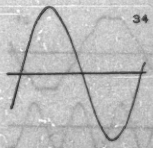
CURVE 29.—POTENTIAL WAVE BETWEEN SHAFT AND BEARING.
4500 kv-a., 25 cycles, 2200 volt, two-phase, generator.

CURVE 30.—CURRENT WAVE BETWEEN SHAFT AND BEARING.
9375 kv-a., 60 cycle, three-phase, 5000 volts.

CURVE 31.—POTENTIAL WAVE ON EXPLORING COIL, SPANNING 12 TEETH — FULL POLE PITCH.
1400 kv-a., 50 cycles, three-phase, 10,000 volts.



CURVE 32.—POTENTIAL WAVE ON EXPLORING COIL, SPANNING 1 TOOTH OF 12 SLOTS PER POLE.
1400 kv-a., 50 cycles, three-phase, 10,000 volts.

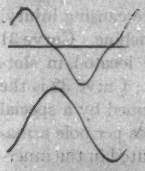


CURVE 34.—POTENTIAL WAVE — FULL LOAD UNITY POWER FACTOR
18 kv-a., 25 cycles, 750 rev. per min., three-phase, 110 volts—pole face 7¼ in. radius

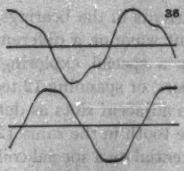
are found to exist are often useful, as are those on special coils made for the purpose. Curve 29 shows potential between shaft and bearing, where currents in the bearings were causing injury. Curve 30 shows current wave on a different machine. Curve 31 is the potential across a special exploring coil located in slots an exact pole pitch apart, or spanning 12 teeth. Curve 32 is the potential between two adjacent slots as determined by a special coil wound around one tooth in the same 12 slots per pole armature. Curve 33 is potential on a special coil located in the innermost slots of a cylindrical rotor (field) of a steam-turbine generator when carrying the single-phase load, and shows the double-frequency e.m.f. induced in the field when single-phase armature reaction is not compensated.

The general effect of load on a generator is to broaden slightly the top of the wave, bending it to the left and making it somewhat unsymmetrical. An inductive load tends to smooth out the harmonics, a condenser load to emphasize them. Curve 34, full-load, unity power factor, should be compared with Curve 5, the no-load wave. Curves 35 and 36 show two curves each, one pair at no load, the other at full load. Curves 37-48, inclusive, show the distribution of the flux in the magnetic field in an 860-kv-a., 60-cycle synchronous motor under different conditions, as generator or motor, at 50 per cent and 100 per cent load, unity power factor, 0.8 lagging and 0.8 leading, the potential waves in all cases being taken on a special coil. These waves are badly saw-toothed or affected by harmonics. This is due to the fact that they represent the potential of a special coil located in two slots only (see Curve 31). The 100 per cent unity power factor load waves are shown on the same oscillograms as the no-load (Curves 37 and 38). This is simply for convenience of comparison. The spacing between the two curves has no relation to the angular displacement produced by load. Curves 49 and 50 are the potential waves at the terminals of the armature winding itself, of the same machine, for the no-load and 100 per cent load, unity power factor conditions. Curves 51 and 52 show the damping effect on harmonics of a unity power factor load in the case of an induction motor tested as generator, where the definite-wound secondary was used for the direct-current excitation.

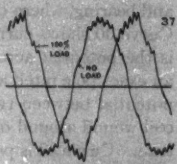
The worst distortion of potential wave is caused by leading current or condenser single-phase load, as a rule. Curves 53 and 54 show the effect of such a load, consisting of underground cable under high-potential test. On the other hand, a poor



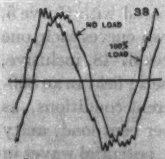
CURVE 35.—POTENTIAL WAVES—NO LOAD.
Upper curve — across one phase. Lower curve —across two phases. 2100 kv-a., 60 cycles, 1800 rev. per. min. three-phase, 2300 volts.



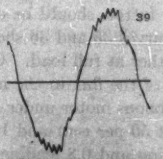
CURVE 36.—POTENTIAL WAVES,—100 PER CENT LOAD — UNITY POWER FACTOR.
Upper curve, across one phase. Lower curve, across two phases. 2100 kv-a., 60 cycles, 1800 rev. per. min., three phase, 2300 volts.



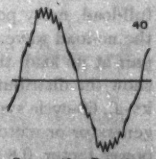
CURVE 37.—POTENTIAL WAVES ON EXPLORING COIL—NO-LOAD, AND 100 PER CENT LOAD—UNITY POWER FACTOR.
860 kv-a., 60 cycles, three-phase, 2300 volts.



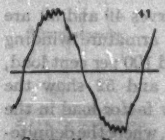
CURVE 38.—POTENTIAL WAVES ON EXPLORING COIL—NO LOAD AND 100 PER CENT LOAD UNITY POWER FACTOR.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



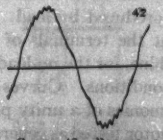
CURVE 39.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD —UNITY POWER FACTOR.
860 kv-a., 60 cycles, three-phase, 2300 volts, as generator.



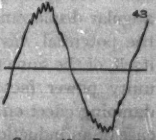
CURVE 40.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD —UNITY POWER FACTOR.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



CURVE 41.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD —0.8 POWER FACTOR LAGGING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as generator.



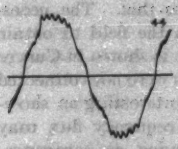
CURVE 42.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD —0.8 POWER FACTOR LAGGING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



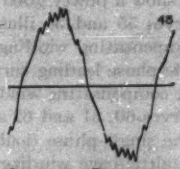
CURVE 43.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD —0.8 POWER FACTOR LEADING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as generator.

wave at no load may show a pretty good wave with single-phase condenser load. Curves 55 and 56 illustrate this. The necessity for providing compensating windings in the field to obtain good waves with single-phase leading current is shown in Curves 57-59, inclusive. The compensating windings were not connected in for Curve 58. Curves 60, 61 and 62 are interesting as showing to what extent the single-phase double-frequency flux may be eliminated by a squirrel-cage winding serving as compensating coils.

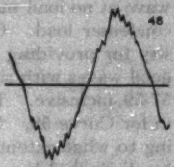
There is considerable deviation from sine wave in many of the synchronous machines in commercial service. Some of them in operation for fifteen or twenty years, have waves as ragged as Curve 55, which was taken on a standard belt-driven, 60-cycle, three-phase generator. Curves 63 and 64 show the no-load potential of two standard 60-cycle, three-phase, 11,000-volt generators of slightly different ratings and speed. Curves 65 and 66 show the waves of two generators, widely different in certain features of design, which are operating in a system of over 100,000 kw. Curve 67 is the wave of an older type of generator operating for several years in parallel with other generators of quite different potential waves in a system of approximately 20,000 kw. The poles of this generator were originally chamfered in a manner similar to that shown in Curve 2. The machine was very noisy when brought to test. The chamfer on poles was changed, with a decided improvement in the matter of noise. Many high-potential synchronous motors with waves showing pronounced harmonics have been operating for years. Curve 68 was taken on a motor where several are in service on a 25-cycle long-distance transmission of approximately 30,000 kw. Approximately 25,000 kw. of motors with waves as in Curve 69 are operating on a 60-cycle system, a long-distance transmission of 35,000 kw. Curves 70 and 71 show waves of star-connected generators that operated in parallel for several years without grounded neutral. Curves 72 and 73 show rather unusual examples of star- and delta-connected generators. Several machines of each type in different places have been in service for nearly ten years. Curve 74 is the wave of a 4800-kv-a. generator in a system of about 25,000 kw. Curve 75 belongs to a plant of 24,000 kw. feeding, through step-up transformers, a 60,000-volt transmission. Curve 76 is the wave of a generator operating with others of different design on a system of approximately 10,000 kw. Curve 77 was taken on a generator operating on a



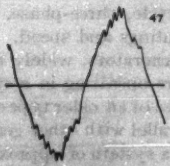
CURVE 44.—POTENTIAL WAVE ON EXPLORING COIL—50 PER CENT LOAD—0.8 POWER FACTOR LEADING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



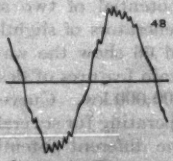
CURVE 45.—POTENTIAL WAVE ON EXPLORING COIL — 100 PER CENT LOAD — 0.8 POWER FACTOR LAGGING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as generator.



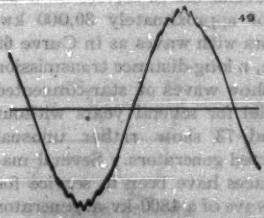
CURVE 46.—POTENTIAL WAVE ON EXPLORING COIL — 100 PER CENT LOAD—0.8 POWER FACTOR LAGGING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



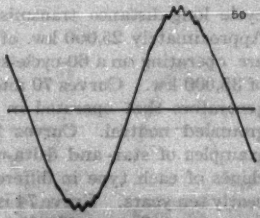
CURVE 47.—POTENTIAL WAVE ON EXPLORING COIL — 100 PER CENT LOAD — 0.8 POWER FACTOR LEADING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as generator.



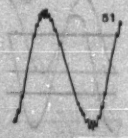
CURVE 48.—POTENTIAL WAVE ON EXPLORING COIL — 100 PER CENT LOAD — 0.8 POWER FACTOR LEADING.
860 kv-a., 60 cycles, three-phase, 2300 volts, as motor.



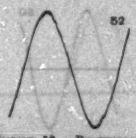
CURVE 49.—POTENTIAL WAVE — NO LOAD.
860 kv-a., 60 cycles, three-phase, 2300 volts.



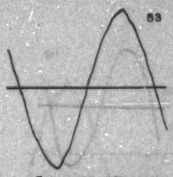
CURVE 50.—POTENTIAL WAVE—100 PER CENT LOAD — UNITY POWER FACTOR.
Motor-generator combination of a pair of machines. 860 kv-a., 60 cycles, three-phase, 2300 volts.



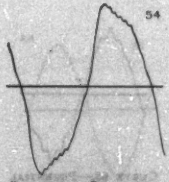
CURVE 51.—POTENTIAL WAVE—NO LOAD.
9 kv-a., 60 cycle, three phase, induction motor, as generator, with d-c. excitation from all three phases of secondary.



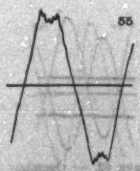
CURVE 52.—POTENTIAL WAVE — 100 PER CENT LOAD.
9 kv-a., 60 cycle, three-phase, induction motor, as generator, with d-c. excitation from all three phases of secondary.



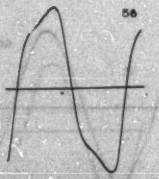
CURVE 53.—POTENTIAL WAVE — NO LOAD.
90 kv-a., 25 cycle, 500 volt, three-phase generator.



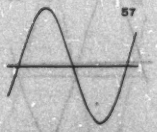
CURVE 54.—POTENTIAL WAVE, SINGLE PHASE, CONDENSER LOAD.
90 kv-a., 25 cycle, 500 volt, three-phase generator.



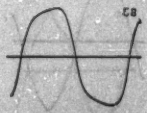
CURVE 55.—POTENTIAL WAVE — NO LOAD.
36 kv-a., 60 cycle, 1150 volt, three-phase generator.



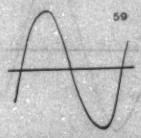
CURVE 56.—POTENTIAL WAVE — SINGLE PHASE—CONDENSER LOAD.
36-kv-a., 60-cycle, 1150-volt, three-phase, generator.



CURVE 57.—POTENTIAL WAVE—NO LOAD.
50 kv-a., 60 cycle, cylindrical rotor, single-phase alternator.

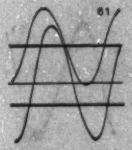


CURVE 58.—POTENTIAL WAVE — CONDENSER LOAD.
50 kv-a., 60 cycle, cylindrical rotor, single-phase alternator—compensating coils in field inactive

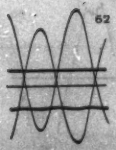


CURVE 59.—POTENTIAL WAVE — CONDENSER LOAD.
50 kv-a., 60 cycle, cylindrical rotor, single phase alternator, compensating coils in field active.

CURVE 60.—POTENTIAL WAVE — NO LOAD.
625 kv-a., 60 cycle, 2100 volt, single-phase generator.

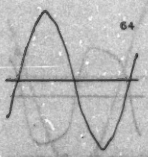


CURVE 61.—OSCILLOGRAMS, UNITY POWER FACTOR, THREE-PHASE LOAD.
Upper curve, armature current. Middle curve, armature voltage. Lower curve, field current. (Upper curve, separate exposure) 625 kv-a., 60 cycle, 2100 volt, single-phase generator.

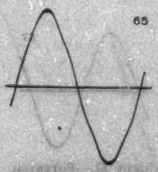


CURVE 62. — OSCILLOGRAMS, 100 PER CENT LOAD, UNITY POWER FACTOR.
Upper curve, armature current. Middle curve, armature voltage. Lower curve, field current.

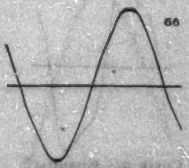
CURVE 63.—POTENTIAL WAVE — NO LOAD.
600 kv-a., 60 cycle, 600 rev. per. min., three-phase, 11,000 volts.



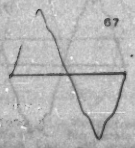
CURVE 64.—POTENTIAL WAVE — NO LOAD.
650 kv-a., 60 cycle, 514 rev. per. min., three-phase, 11,000 volts.



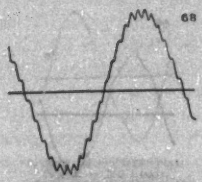
CURVE 65.—POTENTIAL WAVE—NO LOAD.
4500 kv-a., 25 cycle, 250 rev. per. min., two-phase, 2200 volts, external field generator.



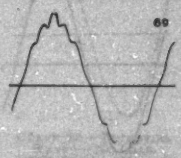
CURVE 66.—POTENTIAL WAVE—NO LOAD.
4500 kv-a., 25 cycle, 250 rev. per min., two-phase, 2200 volt, internal field generator.



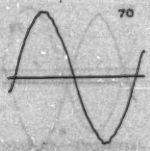
CURVE 67.—POTENTIAL WAVE — NO LOAD. 2400 kv-a., 60 cycle, 106 rev. per min., two-phase, 6000 volts.



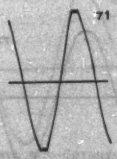
CURVE 68.—POTENTIAL WAVE — NO LOAD. 2100 kw., 25 cycle, three-phase, 13,200-volt synchronous motor.



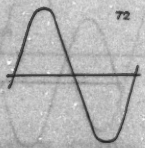
CURVE 69.—POTENTIAL WAVE—NO LOAD. 2100 kw., 60 cycle, three-phase, 11,000-volt synchronous motor.



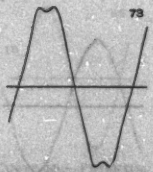
CURVE 70.—POTENTIAL WAVE — NO LOAD. 7000 kv-a., 60 cycle, three-phase, 6900-volt generator.



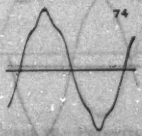
CURVE 71.—POTENTIAL WAVE — NO LOAD. 7000 kv-a., 60 cycle, three-phase, 6900-volt generator.



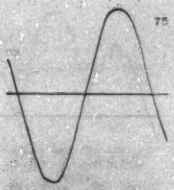
CURVE 72.—POTENTIAL WAVE — NO LOAD. 2800 kv-a., 25 cycle, three-phase, 13,200-volt generator, star connected.



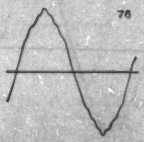
CURVE 73.—POTENTIAL WAVE — NO LOAD. 4200 kv-a., 60 cycle, three-phase, 2300 volt generator; delta connected.



CURVE 74.—POTENTIAL WAVE — NO LOAD. 4800 kv-a., 60 cycle, three-phase, 13,200-volt, generator.

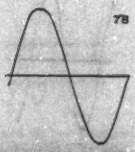


CURVE 75.—POTENTIAL WAVE — NO LOAD. 3000 kv-a., 60 cycle, three-phase, 2300 volt generator.

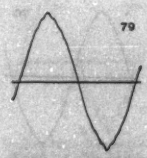


CURVE 76.—POTENTIAL WAVE — NO LOAD. 2400 kv-a., 25 cycle, three-phase, 5000 volt generator.

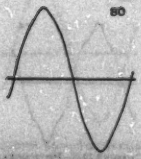
CURVE 77.—POTENTIAL WAVE —NO LOAD. 4200 kv-a., 60 cycle, three-phase, 11,000 volts.



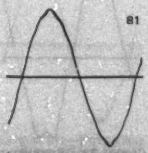
CURVE 78.—POTENTIAL WAVE — NO LOAD. 3000 kv-a., 40 cycles, three-phase, 4400 volt generator.



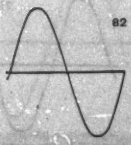
CURVE 79.—POTENTIAL WAVE — NO LOAD. 12,000 kv-a., 60 cycle, three-phase, 11,000 volt generator.



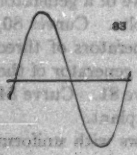
CURVE 80.—POTENTIAL WAVE — NO LOAD. 3000 kv-a., 60 cycles, 360 rev. per min., three-phase, 6600-volt generator.



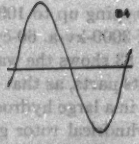
CURVE 81.—POTENTIAL WAVE — NO LOAD. 3000 kv-a., 60 cycle, 164 rev. per min., three-phase, 6900 volts.



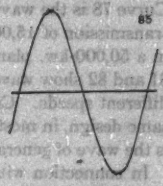
CURVE 82.—POTENTIAL WAVE — NO LOAD. 3000 kv-a., 60 cycle, 133 rev. per min., three-phase, 2300 volts.



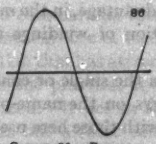
CURVE 83.—POTENTIAL WAVE — NO LOAD. 3600 kv-a., 60 cycles, three-phase, 4000 volts.



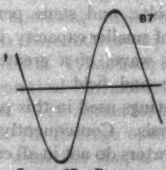
CURVE 84.—POTENTIAL WAVE — NO LOAD. 9000 kv-a., 25 cycle, 375 rev. per min., three-phase, 6600-volt generator.



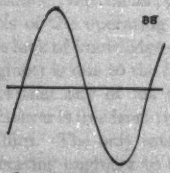
CURVE 85.—POTENTIAL WAVE — NO LOAD. 9000 kv-a., 25 cycle, 750 rev. per min., three-phase, 13,200 volts.



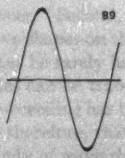
CURVE 86.—POTENTIAL WAVE — NO LOAD. 5555 kv-a., 25 cycle, 1500 rev. per min., three-phase, 13,200 volts.



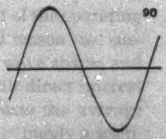
CURVE 87.—POTENTIAL WAVE — NO LOAD. 14,000 kv-a., 60 cycle, 720 rev. per min., three-phase, 4600 volts.



CURVE 88.—POTENTIAL WAVE — NO LOAD. 2500 kv-a., 25 cycle, 1500 rev. per min., three-phase, 2300 volts.



CURVE 89.—POTENTIAL WAVE — NO LOAD. 9375 kv-a., 60 cycle, 1800 rev. per min., three-phase, 5000 volts.



CURVE 90.—POTENTIAL WAVE — NO LOAD. 9375 kv-a., 30 cycle, 1800 rev. per min., three-phase, 7200 volts.

system extending over a vast area with several generating plants. Curve 78 is the wave of a generator in one plant of a 30,000-volt transmission of 15,000 kw. Curve 79 is the wave of a generator in a 50,000-kw. plant stepping up to 100,000 volts. Curves 80, 81 and 82 show waves of 3000-kv-a. 60-cycle generators of three different speeds. Curve 83 shows the wave of a generator of the same design, in most of its parts, as that of Curve 81. Curve 84 is the wave of generators in a large hydroelectric plant.

In connection with cylindrical rotor generators with uniform air gap the distributed field winding serves the same purpose as the shaping of pole in shading the flux in air gap. This class of machines has the advantage of a greater distribution of the armature winding. Curves 85-90, inclusive, are examples of steam-turbine generators of comparatively recent designs. Curve 85 is on a generator at 750 rev. per min. and is not quite so good as Curve 86 on a 1500-rev. per min. generator of the same potential, 13,200 volts, and same periodicity, 25 cycles. Although the latter is of smaller capacity, it has the advantage, in the matter of potential wave, of a greater distribution of windings in both armature and field.

The ratings used in this paper are on the single or continuous rating basis. Consequently, the ratings on the name-plates of the generators do not in all cases agree with those here used.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

WAVE FORM DISTORTIONS AND THEIR EFFECTS ON ELECTRICAL APPARATUS

BY P. M. LINCOLN

While the general question of wave shapes has given rise to comparatively little discussion among operating engineers, it has received considerable attention from those interested purely in the theoretical side of electric engineering. It has been in the past a question that has attracted the theoretical man and student rather than the practical operating man. The reason for this is not far to seek. It lies in the fact that the average operating engineer has but a faint conception of what the shapes of his e.m.f. and current waves are really like. This lack of knowledge is due to two reasons: First, to the fact that there is no ready and inexpensive method of determining wave shapes. Determination of wave shapes requires the use either of an oscillograph or some point-by-point-contact method, either of which is rather expensive, and difficult of operation, as compared to an ammeter, voltmeter, wattmeter, power factor meter, etc., that are every-day tools of the operating engineer. Second, and more important, this lack of knowledge of wave shapes on the part of the operating engineer is due to the fact that he rarely has had reason to suspect that any of his troubles can be traced to wave shape, and whatever is free from trouble-breeding has but little direct interest to him. The only interest, therefore, that attracts the average operating engineer to the study of wave shapes is purely a scientific one, and as a rule this is not a sufficient incentive to cause him to spend the time and money that such a study would entail. The fundamental truth in the old saying "what we don't know, doesn't hurt us" is undoubtedly at the bottom of his indifference in this matter.

This indifference is more or less justified, since there are but few cases on record where distortion of wave forms has actually given rise to difficulties. It is, however, quite possible that wave shape distortion may cause serious trouble in electric circuits, and it is the object of this paper to discuss the question of wave form in some of the aspects that the operating engineer might be expected to meet in the discharge of his regular duties.

The sine form of wave has always been recognized as the standard. The reason for recognizing the sine rather than some other shape of wave as the standard, is sufficiently obvious and so well known as to need no discussion in this paper. Unfortunately, however, not all wave shapes are of the sine form. As is well known, any electrical wave, no matter how much distorted, may be viewed as being made up of a pure sine wave of fundamental frequency upon which are superposed other pure sine waves of a higher frequency, usually called harmonics. That is, any shape of wave may be taken as being made up of a multiplicity of pure sine shapes.

The origin of all the wave shapes which occur in any alternating-current system lies in the shape of the e.m.f. wave of the generators. The shape as determined by the generator may be modified by other synchronous apparatus, as will be indicated later in this paper.

The Standardization Rules of the Institute state that the generator e.m.f. waves shall not depart from the sine shape by more than 10 per cent. The present form of the rule is not entirely satisfactory, since it does not penalize the higher frequency harmonics as much as they deserve. A 10 per cent deviation on the part of one of the higher harmonics is admittedly more dangerous than the same deviation on the part of a lower harmonic, but the existing rule does not recognize this. A modification of the existing rule so as to obtain such a recognition is desirable.

Current waves, as a rule, deviate from the sine form much more than e.m.f. waves. There are various kinds of circuits through which the e.m.f. of a generator may cause a current to circulate. These may be classified as, first, pure resistance; second, pure inductance; third, pure capacity, and fourth, any combination of these three, either in shunt or in series. Arc lighting and rectifier circuits are not considered.

The influence of these various kinds of circuits on the current wave that is caused by a given form of e.m.f. wave will be as follows:

First, a pure resistance will have no effect whatever upon the current wave; that is, the shape of the current wave will be exactly the same as the e.m.f. wave which causes it.

Second, a pure inductance will tend to dampen out the higher harmonics in the current wave. If we have a pure inductance, therefore, we may expect that the current wave will be less distorted than the e.m.f. wave which causes it. The dampening out of the higher harmonics is in proportion to the value of the harmonics. For instance, the third harmonic in the e.m.f. wave will be reduced to one-third value in the resulting current wave, the fifth e.m.f. harmonic, to one-fifth in the current wave, the seventh, to one-seventh, etc. This result follows immediately from the consideration that the impedance offered by a pure inductance increases directly as the frequency.

Third, the effect of a capacity is exactly opposite to that of an inductance. It tends to exaggerate the harmonics in a current wave resulting from a given e.m.f. wave. Also, the amount of the exaggeration is in exact proportion to the order of the harmonic. The third harmonic appears in the current wave as three times its value in the e.m.f. wave; the fifth harmonic, as five times, and the seventh harmonic, seven times, etc. For this reason the current waves that are taken by any condenser, such as, for instance, an empty transmission line, are as a rule very much distorted.

Fourth, a complex circuit consisting of any possible combination of the above simple circuits may have its current wave either smoothed out or exaggerated, depending upon the predominance of the particular kind of impedance contained. The unloaded transmission line is about the only kind of pure capacity that is met with in practical work. All other circuits are made up of resistance and inductance only. Further, in most operating circuits, inductive reactance predominates over resistance, so that there is a tendency to smooth out the current waves. This applies, of course, only to circuits with pure resistance and inductance, which is not the case when synchronous apparatus is in use, nor when saturation of iron circuits exists in the inductance, as, for instance, in transformer magnetizing currents.

The most important case, so far as distortion of wave forms is concerned, is in a circuit which contains synchronous apparatus, such as synchronous motors or converters, and such a circuit is not included in the foregoing classification. Circuits containing pure resistance, inductance or capacity, or complex circuits

containing any combination of these, have no inherent wave form of their own; they receive whatever wave form is applied to them and their action in modifying the generator wave form, if any, is an indirect one. All synchronous apparatus, however, has a distinctive wave form of its own which may be very different from the generator wave form, and usually is at least slightly different. Not only is the shape of the current wave affected by the presence of synchronous apparatus, but also the e.m.f. waves of both the generator and the synchronous apparatus. The final wave form is the resultant of the action of all the synchronous apparatus on a given system.

Perhaps the best way of studying this matter is to assume a concrete case and study that case in detail. Let us assume, therefore, that we have a generating system that has a pure sine

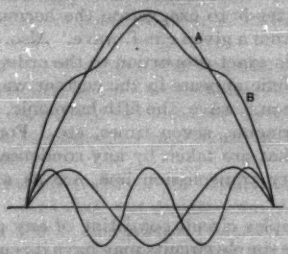


FIG. 1

wave as indicated in curve A, Fig. 1. Let us assume, further, that we have operating on this system a synchronous motor that has a distorted wave form as shown in curve B, Fig. 1. In this case the distortion of wave B is made up by superposing a third harmonic of 10 per cent and a fifth harmonic of 10 per cent on a fundamental sine wave of 99 per cent. When harmonics are superposed on a fundamental the effective value of the resultant wave is the square root of the sum of the squares of the effective values of the various component sine waves. Thus the effective value of curve B is

$$\sqrt{(99)^2 + (10)^2 + (10)^2} = 100$$

The effective value of curve B is therefore exactly the same as A. Let us assume further that the synchronous motor with wave

shape B has zero losses and that its field adjustment is such that its voltage before being synchronized is exactly the same as the supply circuit. If it were not for the difference in wave forms, these assumptions would result in no current flow in the motor, since it would oppose an e.m.f. exactly equal and opposite to the supply e.m.f. at every instant. However, with differing wave forms shown in Fig. 1, this is far from the case. Inspection will show at once that there are instantaneous e.m.fs. in the motor wave that are entirely unopposed by the e.m.f. of the generator wave. From our assumptions as to the amounts of wave form differences it follows that the value of the unopposed fundamental frequency is one per cent, and of the third and fifth harmonics 10 per cent each. If there is no deformation of either the generator or motor waves, the only thing that will oppose the flow of current due to these unopposed e.m.fs. will be the impedance of the circuit composed of generator armature, motor armature, leads, cables, etc. The inductive reactance of such a circuit is so large as compared with its resistance that the flow of current is governed by inductive reactance. Currents will therefore flow due to these e.m.fs., and the value of this current is directly in proportion to the amount of this differential e.m.f. and inversely proportional to its frequency. Suppose we assume, further, that normal voltage at fundamental frequency will cause fifteen times full-load current to flow in the motor armature and that the motor is small compared to the system upon which it operates. The differential e.m.fs. between curves A and B will then give rise to a fundamental frequency current of 15 per cent, a third harmonic current of 50 per cent and a fifth harmonic current of 30 per cent, or a total resultant current of over 60 per cent of full-load. Although the assumptions made would result in no current flow if the wave shapes were the same in motor and generator, the assumed difference in wave shapes gives rise to a circulating current of 60 per cent of full-load. Fig. 2 indicates the theoretical shape of the current wave resulting from these assumed conditions. It will be seen that the current wave is made more distorted than either of the voltage waves of which it is the resultant.

A source of considerable error in our theoretical calculations is the assumption of a constant fixed inductance in the armature circuits of both motor and generator. This assumption is not strictly true, since the inductance will vary to a considerable extent, depending on the angular position of the field.

The reluctance of the magnetic path for the flux set up by the armature current varies with the position of the field; sometimes the minimum air gap between pole face and armature is included in the magnetic path and sometimes the much larger gap of the interpolar space is included. This cyclic variation of reluctance may give rise to a still further distortion of the circulating currents.

In the foregoing it is assumed that the inherent wave forms of both motor and generator remain unaffected by the currents that circulate in their armatures. This is far from being an admissible assumption. In the modern synchronous machines, full load current in the armature has some 50 per cent to 100 per cent of the magnetomotive force of normal field, that is, the field that gives normal voltage at no load. It is at once apparent, therefore, that the instantaneous value of the current that circu-

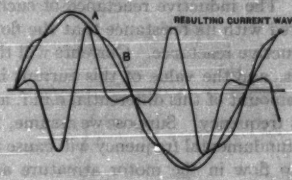


Fig. 2

lates in the armature of a synchronous machine has a very considerable influence over the magnetic flux at that instant and thereby over its wave form. For instance, look at the condition that is shown in Fig. 2. Here the effective value of the current is, as we have seen, 60 per cent of full-load and hence it has a value in setting up magnetic fluxes in the magnetic circuit of the synchronous motor equal to 30 per cent to 60 per cent of the normal field. The actual field strength at any instant is of course the resultant of all the magnetizing forces acting at that instant, and hence the variation in field strength from instant to instant will be very considerable. The direction of this field form variation will of course be such as to oppose the flow of armature current which produces it.

Therefore the inductive reactance of the armature circuit is not the only influence that limits the flow of current due to differences in e.m.f. wave forms. The relative values of these two

influences will depend to a large extent upon the construction of the field of motor or generator. As we have seen, superposed harmonics in the armature circuit will tend to cause rapid fluctuations in the magnetic fluxes of our motor. If the construction of the field is such that there is little opposition to these fluctuations, they will extend throughout the entire magnetic circuit. If, however, as is usually the case, the field structure is provided with "dampers," there will be currents set up in these dampers tending to oppose the fluctuation on the magnetic circuit. The net result of the harmonic in the armature current and the current that circulates in the dampers will be a "stationary wave" of magnetomotive force that will tend to superpose, on the normal field form, a harmonic flux of the same order of frequency as that in the armature current. This harmonic in the field flux produces a harmonic in the resulting e.m.f. wave, as

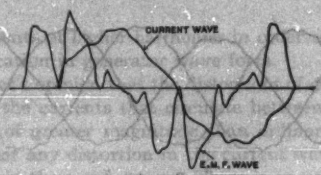


FIG. 3

has been ably shown by Professor C. A. Adams in various papers that he has presented before the Institute.

A striking example of how an e.m.f. wave may be distorted by the effect of armature current recently came to the writer's attention. A 9000-kw. three-phase transformer was under test. The magnetizing current required amounted to some 500 or 600 kv-a. and the iron loss to some 60 or 70 kv. The test was being run from a 750-kv-a. generator. The behavior of the transformer, particularly in regard to noise, led to an investigation of the wave forms. Fig. 3 shows both the e.m.f. and current waves that were taken by the transformer. Fig. 4 shows the open-circuit e.m.f. wave form of the generator. It seems almost unbelievable that this amount of armature current could cause a distortion in the e.m.f. wave from that shown in Fig. 4 to that shown in Fig. 3, but this is an actual determination of wave forms, not a theoretical one.

This 750-kv-a. generator has nine slots per pole and its air

gap is only about 40 per cent of the width of one slot. This condition gives rise to quite a noticeable tooth ripple. A careful analysis, however, shows that this wave contains comparatively small harmonics. The third and fifth are approximately two per cent each, and no other harmonic reaches a value of one per cent. The 17th, 19th and 21st vary from 0.6 to 0.95 per cent and apparently make up the ripple.

Subsequent tests on this transformer were carried out on a 5000-kv-a. generator with an open-circuit e.m.f. wave form as shown in Fig. 5. Both e.m.f. and current wave when exciting the 9000-kv-a. transformer are shown in Fig. 6. In this case the generator is so large that the exciting current for the 9000-kv-a. transformer causes practically no distortion.

In this connection, it may be well to call attention to a fundamental difference in the action of an a-c. generator

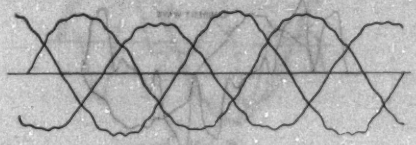


FIG. 4

as compared with a synchronous converter. This fundamental difference must necessarily result in circulating currents of higher harmonic frequencies. An a-c. generator, as we have seen, has a pronounced armature reaction. This armature reaction may be resolved into two components, one of which is demagnetizing to the degree that the generator carries wattless or inductive load, and the other cross-magnetizing to the degree that the generator carries true or real load. The demagnetizing component causes some field distortion and therefore wave form distortion, on account of the fact that the field form caused by the magnetizing action of the armature windings is of a different shape from that caused by the field windings. The cross-magnetizing effect, however, causes a much more marked distortion of the field form, since it causes a marked decrease in magnetic flux at one pole tip and a marked increase at the other. It is the cross-magnetizing effect, therefore, that causes the most pronounced field form distortion and, therefore, wave distortion. This cross-magnetizing effect is entirely absent

in synchronous converters, and therefore their wave forms do not become modified due to true load in the same manner as a-c. generators. As the true load on an a-c. generator varies, its wave form may be distorted. There is no equivalent distortion of the wave forms of the synchronous converters with changes in their loads. It follows, therefore, that there must be some

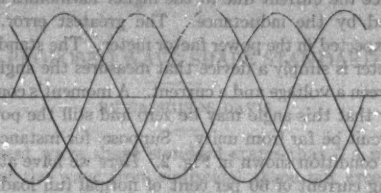


FIG. 5

circulating currents of higher harmonics in order to compensate for this modification in generator wave form.

It is the writer's opinion that the distortions of current waves, particularly in the currents that circulate between synchronous apparatus, are of greater magnitude than ordinarily supposed. It is evident that any distortion in the current wave is reflected to some extent in the e.m.f. wave. There is no particular harm

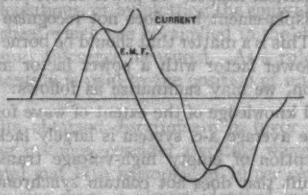


FIG. 6

resulting from these distortions except that the losses are somewhat increased.

The effect of superposed higher harmonics in current and voltage waves so far as the standard types of meters are concerned, deserves some discussion. The standard types of voltmeters, ammeters and wattmeters are not appreciably affected by wave form. This holds true no matter whether the actuating principle is magnetic attraction or heating. Each type integrates over the

wave so as to obtain an indication depending on the r.m.s. or effective value.

Frequency meters of the vibrating reed type are unaffected, since they respond to the fundamental frequency only. The type that balances the pull of a current through a resistance against that of a current through an inductance is subject to a slight error, since the current due to the higher harmonics is partially suppressed by the inductance. The greatest error, however, may be expected in the power factor meter. The standard power factor meter is simply a device that measures the angle of lag or lead between a voltage and a current. A moment's consideration will show that this angle may be zero and still the power factor of the circuit be far from unity. Suppose, for instance, we consider the condition shown in Fig. 2. Here we have at no-load a circulating current of 60 per cent of normal full load. Even if we had full load on the motor and adjusted the field so that a power factor meter showed 100 per cent, we would still have the 60 per cent current (or at least that part of it caused by the third and fifth harmonics—by far the larger part), shown in Fig. 2, superposed on the current that represents true energy. One-hundred per cent power factor is that condition where the kilovolt-amperes and the kilowatts are equal—have a ratio of unity—and it is manifest that this condition can never occur unless the e.m.f. and current waves not only have no angular displacement but also are of identical shapes. A power factor meter recognizes the angular displacement but does not recognize differences in wave shape. This is a matter that should be borne in mind when determining power factor with a power factor meter.

In conclusion, we may summarize as follows:

First, actual knowledge of the extent of wave form distortions existing on the average a-c. system is largely lacking. Second, with the exception of empty high-voltage transmission lines, the usual circuit that does not contain synchronous apparatus has a tendency to smooth out the harmonic in a current wave that is caused by a given e.m.f. wave.

Third, when two synchronous machines of different wave forms are operated on the same circuit, harmonics in the current waves are bound to appear and these currents have a marked tendency toward modifying the e.m.f. waves of all the synchronous apparatus through which they circulate.

Fourth, the indication of power factor meters cannot be taken at face value when harmonic currents flow.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

A PROPOSED WAVE SHAPE STANDARD

BY CASSIUS M. DAVIS

The present wave shape standard states that "a maximum deviation of the wave from sinusoidal shape not exceeding 10 per cent is permissible," where the deviation has to be determined by measurements from an oscillogram or a wave form determined from a wave meter.

The objections to this standard may be summarized thus:

1. The use of an oscillograph or a wave meter is required; often neither is available.

2. It is necessary to measure a large number of ordinates on the wave form, from which the equivalent sine wave is calculated.

3. The position of minimum difference between the distorted wave and its sine equivalent must be determined either by repeated trial calculations, or by plotting the equivalent sine wave on a separate sheet which can be applied to the distorted wave and the minimum difference measured. As a rule, in practical work, little attention is paid to the position of minimum difference.

4. The results obtained discriminate in favor of the higher harmonics. For instance, consider a voltage wave that consists of a fundamental and 17th harmonic of 10 per cent amplitude. The equivalent sine wave is almost identical with the fundamental and the deviation is approximately 10 per cent. If this wave be impressed upon a circuit containing dielectric capacity, as in the case of a transmission line, the capacity current does not consist of the fundamental and 10 per cent 17th harmonic, but has the fundamental and 170 per cent 17th harmonic. Again, if a voltage wave consists of a fundamental and 3rd harmonic of 10 per cent, while the equivalent sine wave is still nearly

identical with the fundamental and the deviation is about 10 per cent, yet its capacity current into a condenser consists of 100 per cent fundamental and a 30 per cent 3rd harmonic. In the first instance the effective value of the current is 197 per cent, based on the fundamental of current, while in the second case the effective value is about 105 per cent on the same basis, and in both cases the deviation of the voltage wave is the same. If these same voltage waves be impressed upon an inductive circuit the opposite effect is produced and the currents have a larger effective value when lower harmonics are present. Now, however, the effective values tend to approach 100 per cent and the distortion does not become so important.

To overcome the above objections, a revision of the rule governing permissible wave shape distortion is suggested which shall take into account the various harmonics of a wave in proportion to the maximum effect which they respectively can produce.

The objection noted under (4), relative to the increase of capacity current taken by a condenser, serves as the basis for one way of determining wave shape distortion. The capacity current of a condenser is proportional to the frequency and the applied e.m.f.; thus when a distorted voltage wave, consisting of a fundamental and its harmonics, is impressed upon a condenser, the effective current is greater than for a sine wave of the same effective value, and furthermore, it is greater in a definite proportion the greater the amplitude and the frequency of the harmonics. In other words, the apparent reactance of a condenser is less on a distorted wave than it is on a sine wave. Thus, we may measure wave shape distortion by the ratio of the reactance of a given condenser on a sine wave to the reactance of the same condenser on the distorted wave, and the permissible wave shape distortion may be defined by assigning a definite value to the ratio. This method of determining the distortion takes into account all harmonics in exact proportion to their amplitudes and frequencies, and gives a measure of the maximum effect which a distorted wave can have on a circuit.

Since the harmonics which are liable to occur in electrical apparatus are of smaller amplitude the higher their order, it is possible to say that their probable amplitude is expressed as a/n per cent of the fundamental, where n is the order of the harmonic and a is a constant. If we assign a value to the distortion ratio mentioned above, and assume there are a given number of harmonics present, a has a definite value. It is only necessary

then to determine the distortion ratio which is permissible in commercial electrical apparatus to fix a fair value for a. This has been done in a preliminary way and the average of tests on 22 commercial alternators gives a distortion ratio of 1.135, which, assuming there are five odd harmonics present besides the funda-

TABLE I.

Values of a for the first m consecutive odd harmonics.

δ	m						
	1	2	3	4	5	6	7
1.05	0.342	0.236	0.191	0.163	0.146	0.133	0.123
1.10	0.493	0.340	0.274	0.236	0.210	0.191	0.176
1.15	0.615	0.423	0.341	0.293	0.261	0.237	0.219
1.20	0.724	0.497	0.400	0.343	0.305	0.278	0.255

mental, gives a a value from 0.242 to 0.246.

The constant a has a series of values depending upon which five harmonics are present. The accompanying Table I shows the values which a may have when there are the first m odd harmonics present, and Table II gives the values of a when

TABLE II.

Values of a for the last m consecutive odd harmonics, assuming the 25th to be the highest probable harmonic in commercial generating apparatus.

δ	m						
	1	2	3	4	5	6	7
1.05	0.320	0.227	0.185	0.160	0.143	0.131	0.121
1.10	0.459	0.324	0.265	0.229	0.205	0.187	0.174
1.15	0.568	0.402	0.328	0.284	0.254	0.232	0.216
1.20	0.664	0.470	0.383	0.332	0.297	0.271	0.251

NOTE: Attention is called to the fact that for a given number of harmonics the values of a lie within relatively narrow limits, as may be noticed by comparing Tables I and II

there are the last m odd harmonics present, assuming the 25th as the highest probable harmonic present in commercial waves.

Where the distortion ratio is to be determined on alternators, and other apparatus subject to load, it should be measured at no load. It is recognized that any load may change the wave shape; but since its character may vary widely, no definite conditions

can be specified under which a load distortion ratio might be taken. With a load of synchronous machines, no specification of the generator wave shape can be made, as it depends more or less on the wave shape of the synchronous motor or converter, and in such a case the wave shapes of the generator as well as the synchronous motor or converter would have to be considered; the wave shape of the circuit being a combination of the two.

On non-inductive load the wave shape is generally rather immaterial; on inductive load it is more sinusoidal, due to the suppression of higher harmonics by the reactance, hence an exaggeration of wave shape distortion over that observed at no-load can be expected only from a load with leading current,

TABLE III.

Amplitudes of harmonics for various values of a. Values are in per cent.

Harmonic	a			
	0.20	0.25	0.30	0.35
3rd	6.67	8.33	10.00	11.67
5th	4.00	5.00	6.00	7.00
7th	2.86	3.57	4.29	5.00
9th	2.22	2.78	3.34	3.89
11th	1.82	2.27	2.73	3.18
13th	1.54	1.92	2.31	2.69
15th	1.33	1.67	2.00	2.34
17th	1.18	1.47	1.76	2.06
19th	1.05	1.32	1.58	1.84
21st	0.95	1.19	1.43	1.67
23rd	0.87	1.09	1.30	1.52
25th	0.80	1.00	1.20	1.40

as a transmission line or cable system. As the proposed method of wave shape specification by the current flowing in a condenser exaggerates the distortion of the no-load wave in the same manner as a leading current load does, the proposed method specifies the no-load wave shape in such a manner as to give weight to the probable distortion which may be expected with a leading current load, and thus appears to make wave shape tests under load unnecessary. It is difficult to load large machines non-inductively, impractical to load them inductively and almost impossible to give them a condenser load. Therefore the proposed method of wave shape specification, which in the no-load wave gives the maximum distortion probable under any kind of load, appears especially suitable.

The apparatus necessary to measure voltage wave shape distortion is very simple. It may consist of a portable set made up of a condenser, a reactive coil and a transformer with various taps, and connected as indicated in Fig. 1. The voltmeter and ammeter readings determine the condenser reactance. The reading is first taken when the double-pole double-throw switch is in position 1, and the reactive coil is in series with the condenser. This gives the sine wave reading, since the reactive coil damps out the harmonics and gives practically a sine wave of impressed e. m. f. on the condenser. Then the reactive coil is cut out by throwing the switch to position 2, and the condenser reactance measured with the distorted wave impressed directly upon the condenser. The ratio of the first reactance to the second gives the wave shape distortion ratio. The transformer is necessary

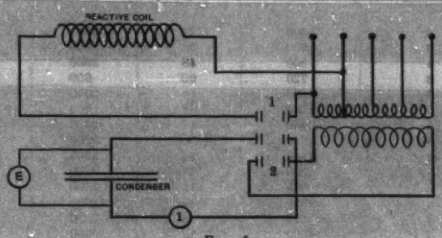


FIG. 1

here in order to give approximately the same voltage across the condenser for either position of the switch.

By a convenient arrangement of switches and transformer taps, a set may be made which could be readily applied to a circuit of any frequency and voltage. The current taken by the set should be less than 5 per cent of the full-load current of the apparatus under test in order not to distort further the wave which is being measured. The reactive coil should be large enough to damp the lowest harmonic, the third, to at least 2.2 per cent of its fundamental, for if it is above this value the distortion ratio would become greater than 1.002, which would introduce an appreciable error.

Of course this method of determining wave shape distortion does not show which harmonics are present, and where this information is necessary the wave form must be found by the oscillograph or the wave-meter, and analyzed.

The accompanying Figs. 2 to 4 show a few of the more distorted waves which have been measured recently by both the present A.I.E.E. method and that proposed in this paper.

In each case the wave has been carefully analyzed and the theoretical and measured distortion ratios compared. Fig. 5 shows a wave which has an exceptionally large distortion ratio.

Using the above as a basis the following are suggested as

TABLE IV

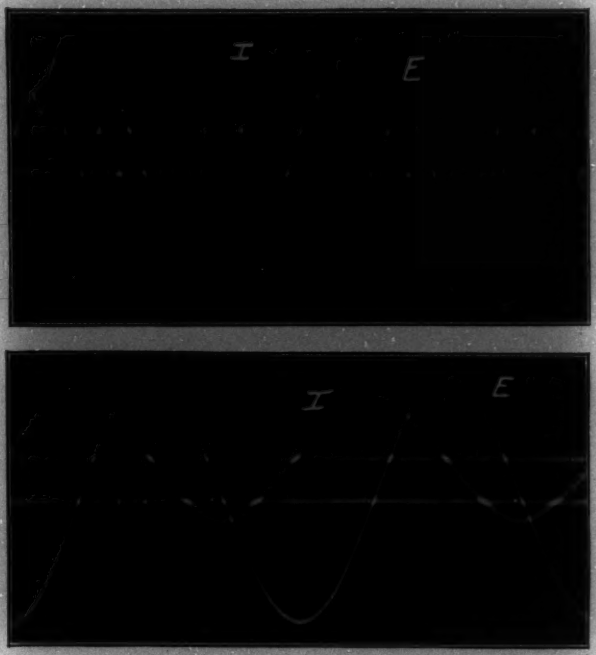
List of alternators upon which the distortion ratio has been measured. Values taken at full voltage and no load. All these machines have a frequency of from 40 to 62½ cycles, and the output is given on a single rating basis.

No. of phases	Kv-a. output	No. of poles	Voltage	Ratio
3	1500	24	2300	1.031
3	900	36	2300	1.014
3	500	48	2300	1.135
3	720	60	600	1.010
3	1600	14	2300	1.047
3	1200	48	600	1.017
3	1440	48	2300	1.068
3	700	10	2200	1.030
2	1440	24	2300	1.017
3	390	48	2200	1.111
2	375	12	2300	1.017
3	1350	14	11000	2.360
3	375	28	2300	1.002
3	4500	12	6600	1.090
3	240	18	600	1.036
3	288	10	2300	1.018
3	450	48	600	1.034
3	300	14	2300	1.022
3	675	32	600	1.001
3	300	60	2300	1.673
3	1200	24	2300	1.238
3	1140	30	2200	1.006

substitutes for the present A.I.E.E. Standardization Rules on Wave Shape Distortion:

The wave shape distortion ratio at no-load should not exceed 1.15, except when otherwise specified.

The distortion ratio is determined by impressing the wave form on a suitable condenser, measuring the reactance offered by such condenser to the flow of current and comparing this reactance to the true reactance of the same condenser as measured with a sine wave of current. The latter may be determined by measuring the condenser reactance on any wave shape with an inductive reactance in series, having less than 10 per cent



[C. M. DAVIS]

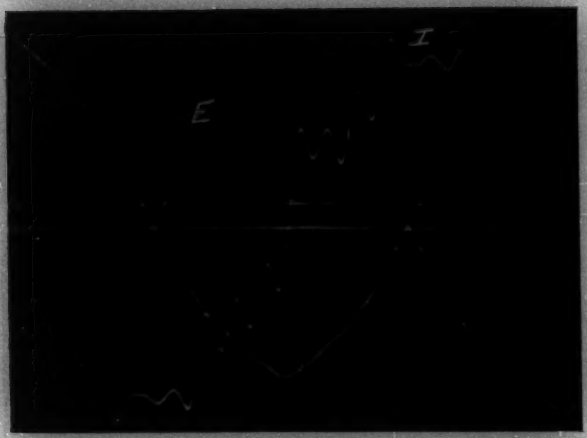
FIG. 2.—WAVE SHAPE OF THREE-PHASE, 500 KV-A., 48-POLE, 2300-VOLT GENERATOR.

Distortion ratio = 1.135. Deviation (by present A. I. E. E. rule) 8.7 per cent.

$$E = 3248 \cos(\theta - 87^\circ) + 172 \cos(5\theta - 87^\circ) + 80 \cos(7\theta - 67^\circ) + 34 \cos(11\theta + 70^\circ) + 39 \cos(13\theta - 43^\circ)$$

$$I = 1.32 \cos(\theta - 83^\circ) + 0.41 \cos(5\theta - 65^\circ) + 0.27 \cos(7\theta - 62^\circ) + 0.11 \cos(11\theta - 27^\circ) + 0.36 \cos(13\theta + 30^\circ)$$

The lower curves show how the same generator voltage wave is smoothed out to nearly sinusoidal shape by the reactive coil in series.



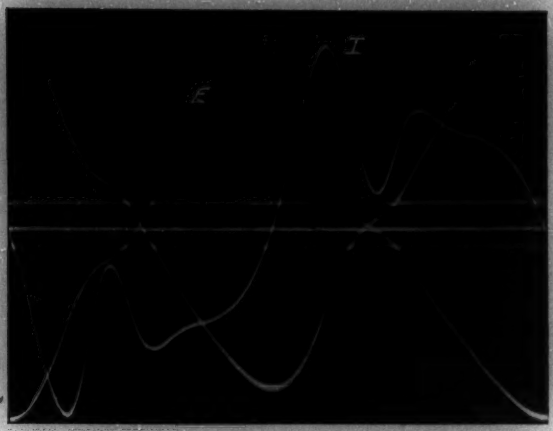
[C. M. DAVIS]

FIG. 3.—WAVE SHAPE OF THREE-PHASE, 45-KV-A., SIX-POLE, 120-VOLT GENERATOR.

Distortion ratio = 1.020. Deviation 5 per cent

$$E = 166.7 \cos(\theta - 90^\circ) + 2.95 \cos(5\ \ + 84^\circ) + 2.04 \cos(7\theta + 85^\circ) + 0.80 \cos(11\theta - 67^\circ) + 0.66 \cos(17\theta + 77^\circ) + 0.49 \cos(19\theta - 69^\circ)$$

$$I = 5.43 \cos(\theta + 87^\circ) + 0.55 \cos(5\theta + 77^\circ) + 0.50 \cos(7\theta + 80^\circ) + 0.37 \cos(11\theta - 68^\circ) + 0.57 \cos(17\theta - 68^\circ) + 0.33 \cos(19\theta - 79^\circ)$$



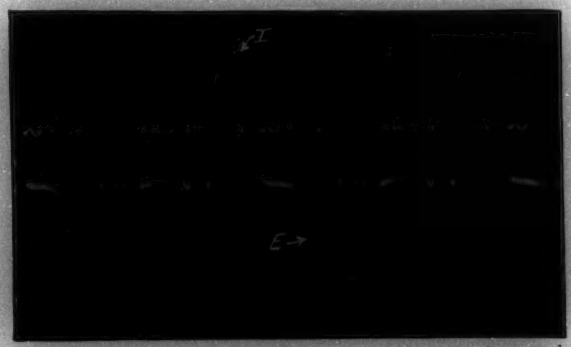
[C. M. DAVIS]

FIG. 4.—WAVE SHAPE OF THREE-PHASE, 10-KV-A., SIX-POLE, 120-VOLT GENERATOR.

Distortion ratio 1.140 Deviation 15.7 per cent

$$E = 166 \cos(\theta - 88^\circ) + 22 \cos(3\theta + 87^\circ) + 8.3 \cos(5\theta - 4^\circ) + 2 \cos(7\theta + 31^\circ) + 1.5 \cos(9\theta - 22^\circ)$$

$$I = 5.41 \cos(\theta + 82^\circ) + 2.04 \cos(3\theta + 85^\circ) + 1.45 \cos(5\theta - 8^\circ) + 0.86 \cos(7\theta - 67^\circ) + 0.23 \cos(9\theta + 55^\circ)$$



[C. M. DAVIS]

FIG. 5.—WAVE SHAPE ILLUSTRATING A VERY BAD DISTORTION RATIO

Distortion ratio = 1.92

power factor and consuming a voltage three or four times that at the condenser terminals. The distortion ratio is the fraction

$$\frac{\text{true condenser-reactance}}{\text{condenser reactance on distorted wave}}$$

Measurements of wave shape distortion on apparatus should be made at full voltage and no-load.

APPENDIX

Derivation of Distortion Ratio

Let x_0 = true reactance of condenser

n = order of the harmonic

E_n and I_n = max. values of voltage and current, respectively, of the nth harmonic

E and I = effective values of the distorted wave.

x_c = apparent reactance of the condenser on the distorted wave.

δ = distortion ratio

a = amplitude constant of the harmonics

m = the number of harmonics present above the fundamental.

Then:

$$I_n = \frac{n E_n}{x_0}$$

$$E = \sqrt{\tfrac{1}{2} \Sigma E_n^2}$$

$$I = \sqrt{\tfrac{1}{2} \Sigma I_n^2}$$

$$x_c = \frac{E}{I}$$

and

$$\delta = \frac{x_0}{x_c}$$

If

$$E_n = \frac{a}{n} E_1$$

$$I_n = \frac{n E_n}{x_0} = \frac{a E_1}{x_0}$$

$$I = \sqrt{\tfrac{1}{2}\left(I_1^2 + m \frac{a^2 E_1^2}{x_0^2}\right)}$$

$$= \frac{E_1}{x_0} \sqrt{\tfrac{1}{2}(1 + m a^2)}$$

$$E = \sqrt{\tfrac{1}{2}\left(E_1^2 + \frac{a^2}{n^2}E_1^2 + \ldots \text{ to } m \text{ harmonics}\right)}$$

$$= E_1\sqrt{\tfrac{1}{2}\left\{1 + a^2\left(\Sigma\frac{1}{n^2}\right)\right\}}$$

$$x_e = \frac{E}{I} = x_0\sqrt{\frac{1 + a^2\left(\Sigma\frac{1}{n^2}\right)}{1 + m\,a^2}}$$

and

$$\delta = \sqrt{\frac{1 + ma^2}{1 + a^2\left(\Sigma\frac{1}{n^2}\right)}}$$

from which

$$a = \sqrt{\frac{\delta^2 - 1}{m - \delta^2\left(\Sigma\frac{1}{n^2}\right)}}$$

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

THE EXPERIMENTAL DETERMINATION OF THE REGULATION OF ALTERNATORS

BY A. B. FIELD

The section of our Standardization Rules* which deals with alternator regulation has remained in force practically unchanged for the past ten years. When this was originally drawn up, it was generally customary to specify the regulation for non-inductive loads, and for this condition, the suggestions contained in the rules are satisfactory; the rules, however, are not explicitly restricted to non-inductive loads, and when at a later date the regulation for lower power factors began to be more frequently the subject of specification, the same methods of computation from test results were naturally followed. It has been somewhat of a superstition for many years, although now rapidly dying out, to put an undue importance upon the regulation of a-c. generating apparatus, upon the equality of regulation of machines which are to run in parallel, and so on. It is now well recognized that greater adaptability of the machine to occasional operation at over-voltage, excess current, and lower power factors, is of more value than a comparatively close regulation, the combination of the two properties being seldom commercially feasible. Other considerations also have arisen which call for higher regulation rather than low. As an illustration of the earlier attitude may be cited the fact that the A. I. E. E. rules for the determination of the regulation have been accepted readily by the same purchasers who specify closely a given regulation and are inclined to base acceptance or rejection of apparatus upon the supposed regulating qualities within a narrow margin, although the *real*

*Section 209 in the 1907 and 1911 editions and Section 71 in the 1902 edition.

regulation on, say, an 80 per cent power factor load, may vary considerably from the figure anticipated by one who applies the methods of Section 209, and the variation is in the direction of higher regulation.

To review the situation very briefly, let us consider the regulation at zero power factor, a characteristic more easily checked experimentally, than the regulation at any other power factor. According to Section 209, we obtain the zero power factor saturation curve from the no-load saturation curve by shifting this over, parallel to itself, a given distance horizontally, the vector addition of excitations being the same as arithmetical addition when the power factor is zero (see Fig. 1). This is equivalent to representing the effect of the load as a simple demagnetizing action on the field magnets, while we know that, to put it at its

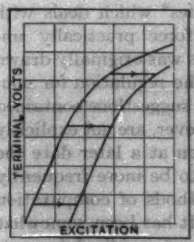


FIG. 1

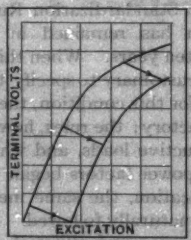


FIG. 2

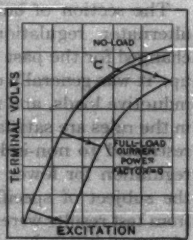


FIG. 3

simplest, we have the combination of a demagnetization and a reactive voltage drop, which would suggest moving the no-load saturation curve over parallel to itself, not horizontally, but in an inclined direction, the inclination being determined by the ratio of reactive drop to the demagnetizing action (see Fig. 2). It should be noted that these two give the same results only for a no-load curve which has no saturation bend.

As a matter of fact, this method again will give an approximately correct result only when the percentage pole leakage is small, or when the load considered produces a demagnetizing effect upon the armature which is small compared with the ampere-turns of the air gap and teeth.

To obtain a closer approximation to the load saturation curve for zero power factor, deduced from the no-load and short-cir-

cuit curves, we must lay out an auxiliary no-load saturation curve with increased pole leakage (curve C in Fig. 3) and move this curve parallel to itself horizontally by an amount corresponding to the armature demagnetizing ampere-turns, and vertically downwards by an amount corresponding to the armature reactive voltage drop. The amount of pole leakage for curve C is determined approximately by considering (A) the armature demagnetizing ampere-turns, and (B) the magnetizing ampere-turns for the air gap plus armature laminations. The ratio

$\frac{A + B}{B}$ is the factor by which the no-load pole leakage is to be multiplied in order to obtain that for curve C. With this procedure the experimentally determined zero power factor saturation can generally be checked fairly closely.

As a matter of fact, the *general shape* of the load saturation curve, within the range that we are usually concerned with, closely resembles that of the no-load saturation curve; that is to say, if the curve be transferred to a piece of tracing paper and laid on top of the no-load curve, a position can be found in which they nearly fit one another. This indicates that by using a *fictitious* armature reaction and reactive voltage drop for the method of Fig. 2, a compromise inclination can be found for the direction in which to move over the no-load curve, and obtain the zero power factor curve. If the curves have been experimentally determined, the inclination can be found readily, by moving the load curve horizontally to the left till it passes through the origin, thus matching the no-load curve over the initial straight part, and then moving it up in the direction of the initial slope until the higher points also agree. This process is followed in Fig. 4, where, taking a fairly high point P on the load curve, we set out $P\,Q$ to the left, equal to $O\,R$, and then draw $Q\,S$ parallel to the initial part of the saturation curve. It will be found that the distances between the two curves measured parallel to $S\,P$ are nearly constant, provided we do not push the method to points too high up on the curves. The distance $O\,R$ is obtained from the direct short-circuit curve for the load current in question, and a few high points on the load curve enable us to construct the curve fairly well.

It should be noticed that the actual drop in voltage on inductive load, with a given saturation and a short-circuit curve, depends upon the inclination of $S\,P$, and therefore is not determinate from the saturation and short-circuit curves alone.

Further information is required, preferably the experimentally determined saturation curve for full-load current at a power factor nearly zero. To illustrate this graphically, there are given in Fig. 5 the no-load and short-circuit curves of two generators which, when plotted to suitable scales, practically coincide. However, the pole leakage of one machine is a more prominent feature than in the case of the second machine, and we have a correspondingly lower load saturation curve. Both machines are of modern type and construction and have the same number of poles, and the curves are plotted from test figures slightly adjusted to bring them to a comparable load basis. It will be seen

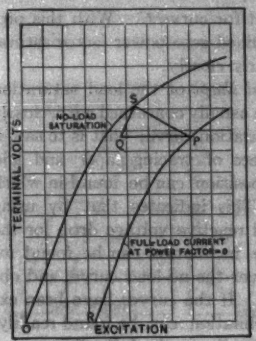


FIG. 4

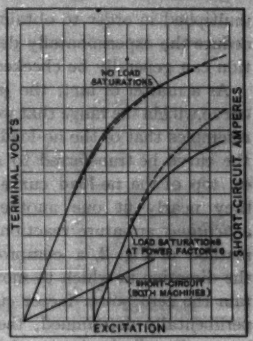


FIG. 5

that, in spite of the coincidence of the no-load and short-circuit curves, the zero power factor curves do not coincide, except on the straight parts at low voltages.

RECOMMENDATIONS

This memorandum upon regulation has been written merely to introduce a discussion upon the subject. In order to have a definite basis to start from, the author suggests that this Institute make the following recommendations:

1. That the regulation of alternators for unity power factor be specified only in those cases in which the actual operation of the plant may be expected to be at a power factor very near unity, and then only when conditions make the regulation a feature of importance.

2. That for alternators which are to operate at power factors of 85 per cent or below, it should be recognized that the actual value of the regulation (which is necessarily high) is of minor importance, and that when it is desired to specify regulation for power factors below 80 per cent, it is preferable to do so for power factor zero, since this can be directly checked experimentally on the manufacturers' test floor in many cases, while the regulation at higher power factors cannot be so checked, except for very small machines. The operating regulation will always be lower than the zero power factor regulation for a given ampere load.

3. That when it is desired to determine experimentally the regulation at a given load, and at power factors between unity and zero, for machines which cannot be actually loaded at the desired power factor, it is preferable to do so from the experimentally determined saturation curves for no-load, and for the given ampere load at zero power factor.

4. That to determine the load saturation curve for a given power factor from these two curves, it may be assumed, for uncompensated alternators, that at any excitation value the drop in voltage between no-load and zero power factor load is equivalent to a reactive drop, which may be treated vectorially for the power factor in question. The armature ohmic voltage drop may similarly be treated vectorially, but generally has a negligible effect upon the regulation at power factors below unity.

5. That for the experimental determination of the load saturation curve at zero power factor, any power factor below 20 per cent may be assumed to be equivalent to power factor zero.

Conclusion

In conclusion, the author wishes to direct attention to a paper* on this subject presented ten years ago, before the Institute, in connection with the revision of the clauses on regulation in the Standardization Rules. That paper drew attention to the importance of the zero power factor curve, and showed the relation between this and the no-load saturation as outlined above. The revision of Section 209 can advantageously be based upon the conclusions submitted there.

**The Experimental Basis for the Theory of the Regulation of Alternators*, by B. A. Behrend, Transactions A. I. E. E., 1903, XXI, p. 497.

2. That for alternators which are to operate at power factors of 85 per cent or below, it should be recognized that the actual value of the regulation, which is proportionally small in all cases of importance, and that which it is desired to suppress, depends for power factors below 80 per cent, it is practicable to do so for power factor zero, since this can be directly obtained experimentally on the manufacturer's floor in many cases, while the regulation at higher power factors cannot be so obtained, except for very small machines. The regulation will always be lower than the zero power factor regulation for a given amount of load.

3. That when it is desired to determine experimentally the regulation at a given load and at power factors between unity and zero, for machines which cannot be actually loaded at the desired power factor, it is practicable to do so from the experimentally determined saturation curve for no-load and for the given amount of load at zero power factor.

4. That to determine the load saturation curve for a given power factor from these two curves, it may be assumed, for numerous alternators, that at any operation value the drop in voltage between no-load and zero power factor load is equivalent to a reactance drop, which may be treated vectorially for the power factor in question. The armature stator reactance drop may similarly be treated vectorially, but generally has a negligible effect upon the regulation at power factors below unity.

5. That for the experimental determination of the load saturation curve at zero power factor, any power factor below 20 per cent may be assumed to be equivalent to power factor zero.

Conclusions

In conclusion, the author wishes to direct attention to a paper* on this subject presented ten years ago before the Institute, in connection with the revision of the clauses on regulation in the Standardization Rules. That paper drew attention to the importance of the zero power factor curve, and showed the relation between this and the no-load saturation as outlined above. The revision of Section 203 can advantageously be based upon the conclusions submitted there.

---

*The Experimental Basis for the Theory of the Synchronous Alternator by B. A. Behrend: TRANSACTIONS A. I. E. E., 1903, XXII, p. 447.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

REGULATION OF DEFINITE POLE ALTERNATORS

BY SOREN H. MORTENSEN

The question of determining regulation of synchronous generators from shop tests has been treated by various authors in the past.* In most cases, it is hardly practicable to determine regulation under actual load conditions. As an alternative, the American Institute of Electrical Engineers has recommended a method of obtaining regulation from no-load saturation, short-circuit characteristics, and armature resistance. However, this method, as has been proved, gives in most cases incorrect results.

The object of this paper is to supply data collected from tests on various machines showing that, with the same tests as needed for the A. I. E. E. method, and very little more work, approximately correct regulation results can be obtained by what may be called the "triangle method." In it, regulation is derived by means of the Kapp diagram from a full-load, zero power factor saturation curve, which in turn has been derived from a no-load saturation and short-circuit curve with the aid of Potier's triangle.

The tables given further on show results obtained by the triangle and the A. I. E. E. methods, as compared with regulation derived from actual full load, zero power factor saturation curve.

To determine Potier's triangle for a machine, when its no-load saturation and short-circuit curves are known, it is only necessary to calculate the magnetomotive force of direct armature reaction, that is, the back ampere-turns per pole. Armature

*B. A. Behrend A. I. E. E. TRANSACTIONS Vol. XXI —1903, p. 497
Hobart and Punga " " " XXIII—1904, p. 291
B. T. McCormick " " " XXIII—1904, p. 330

transverse reaction is practically zero when a machine is run on short circuit. The armature reactance can be found directly from the no-load saturation and short-circuit curves as shown in Fig. 1 ($I\,x$ component).

The generally accepted equation for magnetomotive force of direct armature reaction under purely inductive load, zero power factor, may be expressed as follows:

$$A\,T = 0.9 \times K_s \times K_m \times K_d \times \sin\phi \times N \times I \times T \quad (1)$$

$A\,T$ = Reaction (back ampere-turns) expressed in ampere-turns.

K_s = Factor for fractional stator coil pitch same as for e.m.f calculations.

K_d = Distribution factor taking into account number of slots per pole per phase, same as used for e.m.f calculations.

*K_m = Coefficient of direct reaction.

Sin ϕ = Factor taking into account that displacement between e.m.f. and short-circuit current is not quite 90 deg. due to short-circuit stray losses.

N = Number of phases.

I = Armature current per phase.

T = Number slots per pole per phase

$$\times \frac{\text{No. conductors per slot}}{2 \times \text{No. circuits of arm. wdg.}}$$

For practical purposes, we may substitute mean values for several of the factors found in equation (1) without committing any appreciable error, as variation of these factors is small, as shown below.

The value of sin ϕ was determined for a number of machines from short-circuit stray loss curve, and it was found to vary between 0.97 and 0.99.

K_m is a function of the ratio $\frac{\text{pole arc}}{\text{pole pitch}}$ which, for machines of modern design, generally will fall between 54 per cent and 75 per cent. For these values K_m would vary between 0.885 and 0.78 if the pole face is shaped concentric with armature bore. As the pole face is frequently chamfered, these values have to be modified. From tests on numerous machines of different design,

*For derivation of K_m see Kapp's "Dynamo Machines"—1904.

it has been found that a mean value of 0.79 for K_m gives consistent results. As the variation in the value of the distribution factor K_d for three- and two-phase machines is rather small, a value of $K_d = 0.96$ for three-phase machines, and $K_d = 0.92$ mean for two-phase machines, may be taken.

Single-phase machines are often built on two- or three-phase armature punchings, by leaving certain slots empty. K_d thus varies over a much wider range than is the case for two-phase and three-phase machines, and hence no mean value has been

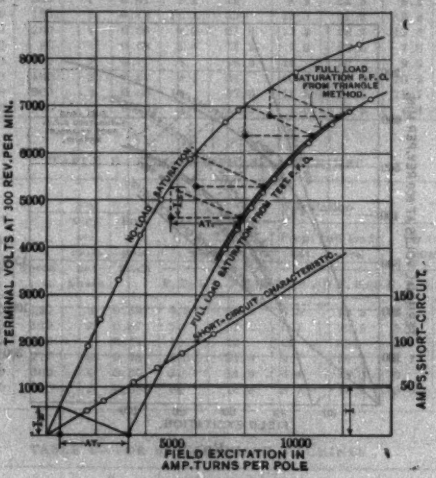


FIG. 1

assumed. By choosing average values as indicated above, we thus obtain the following simple equation for back ampere-turns:

$$A\,T = 2\,I\,T \text{ for three-phase machines} \tag{2}$$

$$A\,T = 1.3\,I\,T \text{ for two-phase machines} \tag{3}$$

$$A\,T = 0.72\,K_d\,I\,T \text{ for single-phase machines} \tag{4}$$

Using the above equations for determining Potier's triangle, the results, shown in tables, were worked up from tests. The full-load saturation, zero power factor curve was determined by sliding triangle along the no-load saturation curve as shown in Fig. 1.

Regulation for power factors given in Tables A, B and C was then derived by means of a Kapp diagram.

For machines with high pole densities and a large field leakage, the triangle method will give more favorable regulation results than will actual tests, since in deriving the load saturation curve from no-load saturation and short-circuit curve, no consideration is taken of increased field leakage due to load conditions.*

Figs. 2 and 3 show curves from machines with high magnetic densities. In Fig. 2, saturation is in armature iron, and here

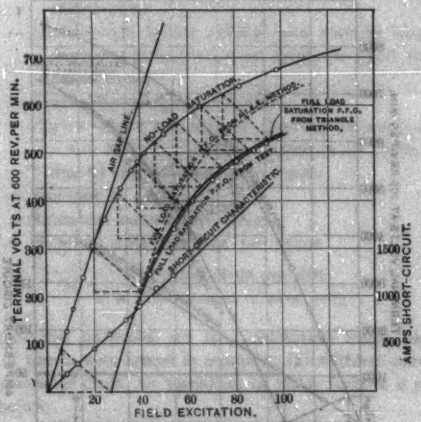


FIG. 2

curves from triangle method and test check each other closely. Fig. 3 is from a machine with an unusually large pole density

*Corrections for load field leakage may be made if, before applying triangle method, the no-load saturation curve is replotted for a field leakage of σ' instead of σ if

σ' = field leakage flux for full-load zero power factor saturation curve.

σ = field leakage flux for no-load saturation curve.

And further

K = constant depending on pole pitch and shape

$A\ T$ = armature back ampere-turns from equation (1)

Then $\sigma = K \times$ ampere-turns for (air gap + armature iron)

and $\sigma' = K \times$ amp.-turns for (air gap + arm. iron + $A\ T$).

TABLE A—FOR THREE-PHASE MACHINES

Rating			No. slots per pole per phase	Pole arc pole pitch	Regulation					
					By A. I. E. E. method		From full load sat. curve		By triangle method	
Kw.	Volts	Speed r.p.m.			P. F. 1	P. F. 0.8	P. F. 1	P. F. 0.8	P. F. 1	P. F. 0. 8
200	2300	1800	4	0.54	11.	23.	11.2	25.	11.2	25.2
600	6600	300	3	0.62	4.3	15.	6.5	17.5	6.2	17.1
2800	2300	720	3	0.685	9.	21.8	10.	24.	9.7	23.6
600	2300	150	4	0.60	7.4	17.4	8.5	24.2	8.3	23.4
250	480	120	2	0.72	8.3	18.6	11.4	27.	10.3	25.5
525	2200	500	4	0.54	16.4	31.	18.2	33.6	17.6	33.
200	2300	200	1	0.61	5.1	19.	8.3	25.5	8.2	24.6
200	2300	150	2	0.72	11.1	25.	13.5	31.2	12.5	30.
500	11000	100	1	0.66	9.2	21.8	12.8	28.2	12.2	27.8
1000	2300	82	1	0.68	6.4	17.2	7.9	23.5	7.6	23.
1750	6600	100	2	0.71	6.	18.2	11.	22.	9.9	21.1
1000	2400	180	3	0.66	9.1	21.	10.6	26.2	10.2	25.2
225	2200	900	2	0.55	10.	22.3	11.8	24.2	11.7	24.1
625	2300	300	2	0.702	3.7	11.5	4.3	16.6	4.4	16.7

TABLE B—FOR TWO-PHASE MACHINES

Rating			No. slots per pole per phase	Pole arc pole pitch	Regulation					
					By A. I. E. E. method		From full load sat. curve		By triangle method	
Kw.	Volts	Speed r.p.m.			P. F. 1	P. F. 0.85	P. F. 1	P. F. 0.85	P. F. 1	P F. 0.85
500	2300	120	2	0.597	4.5	15.6	8.5	19.5	8.	19.5
250	1100	120	2	0.57	5.	17.	5.7	20.5	5.9	20.6
420	125	240	2	0.64	16	33.	20	38.	20	38.
125	440	277	3	0.68	8.5	21.5	9.1	24.8	8.7	23.8
1000	2200	500	6	0.56	5.	14.8	5.4	16.5	6.	17.3
700	2300	120	2	0.598	6.	13.9	8.7	20.4	8.6	20.3

TABLE C—FOR SINGLE-PHASE MACHINES

Rating			No. slots per pole per phase	Pole arc pole pitch	Regulation					
					By A. I. E. E. method		From full load sat. curve		By triangle method	
Kw.	Volts	Speed r.p.m.			P. F. 1	P. F. 0.85	P.F. 1	P.F. 0.85	P. F. 1	P.F. 0.85
			empty							
75	440	250	6—2	0.66	2.7	12.2	5.4	17.9	5.9	18.2
90	2300	900	6—2	0.55	8.8	20.	11.	28.	10.6	27.3
260	2300	150	3—1	0.60	3.	10.4	6.	18.	6.	17.9
160	2200	200	3—1	0.60	11.7	24.	16.	30.	15.	28.9
65	2200	277	3—1	0.62	9.1	20.2	14.	31.5	14.	31.

and a large field leakage. Here, field leakage due to ampere-turns compensating armature reaction causes the load saturation curve to lean over more than indicated by the triangle method. The latter, however, is more accurate than the A. I. E. E. method.

In general, it may be said that results show that the triangle method gives regulation considerably nearer the actual than does the A. I. E. E. method. Moreover, the triangle method is so simple as to be easily applied. Data for use in equations (2), (3) and (4) can be taken directly from a winding specification. No-load saturation, short-circuit curve, and armature resistance are

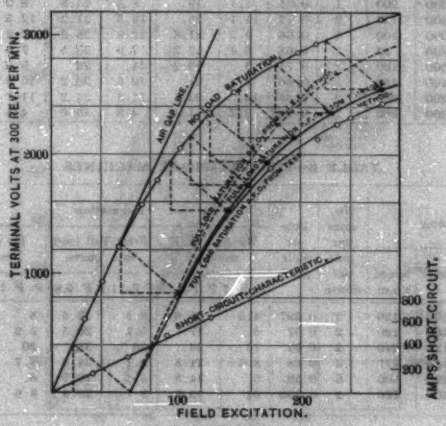


FIG. 3

always available, and the graphical operation involved to get regulation at any power factor is as simple as the present A. I. E.E method. The Kapp diagram can be simplified if the influence of ohmic resistance is neglected. This can be done in most cases without impairing the accuracy of the results.

Thus, it would seem that the triangle method has proved itself sufficiently accurate and also simple enough to be practicable; it might therefore be considered as a fitting substitute for the present A. I. E. E. method.

A paper presented at the Midwinter Convention of the American Institute of Electrical Engineers, New York, February 28, 1913.

Copyright, 1913. By A. I. E. E.

GENERATOR AND PRIME MOVER CAPACITIES

BY DAVID B. RUSHMORE AND ERIC A. LOF

The chief distinctive characteristic of electrical apparatus is that its capacity is limited by thermal considerations. Electrical generators are of necessity driven by prime movers, and the combination must be treated as a single unit when considering the questions of ratings and capacities. Such prime movers as steam engines, steam turbines, gas engines and waterwheels have various limitations regarding their output which must be considered in connection with that of the electric generators they are driving. The proper adjustment of ratings for generators and prime movers with these different limitations as determined by the conditions of service, is the object of this paper. In direct-current generators the limitation imposed by commutation has almost entirely been removed by the use of interpoles. With alternators as now constructed, the limitation of output due to regulation of the machine is but seldom found; therefore the question of heating may be considered as the important factor for consideration. Under certain conditions of violently fluctuating loads or intermittent service, the questions of commutation and regulation may, however, become of considerable importance.

The capacity of an alternator is limited not only by the actual energy load which the machine is carrying, but also by the power factor of such load. The additional heating at low power factors and constant power is due to the wattless component of the armature current and also to the additional field current necessary to counteract it. In many cases it is possible to predetermine approximately the power factor under which the generators will operate, and the special design to meet this

particular condition is largely desirable. The curves in Fig. 1 show the different conditions of load and power factor which will produce the limiting conditions of heating in an inductor alternator. The synchronous impedance here is considered to consist almost entirely of reactance.

The importance of the proper adaptation of capacities of generators and prime movers is emphasized by the fact that there are in operation in many stations in this country units in which the output is unnecessarily limited by an improper rating

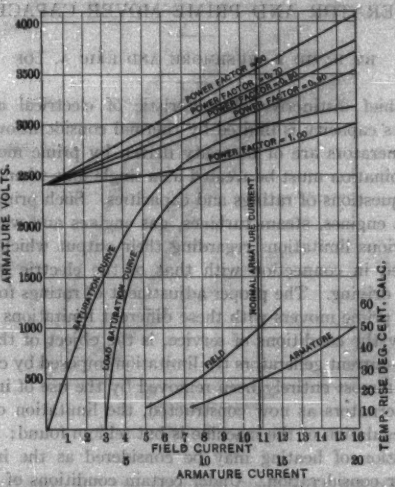


FIG. 1—CHARACTERISTIC CURVES OF INDUCTION ALTERNATOR.

or design of either the generator or prime mover. The generator may be designed for unity power factor while the condition of operation may be the power factor 0.8, in which case only a part of the prime mover capacity can be utilized. In not a few instances in hydroelectric stations, the waterwheel is either too small or too large for the generator and a like result ensues. In some hydroelectric plants where the generators are installed to handle peak loads, this maladjustment of ratings is a necessity, but with most of the larger systems it is unnecessary to run machines

except at or near their maximum ratings. In the past, every effort was made to adjust the ratings of generators to the load curves and we had 25, 50 and 100 per cent overload guarantees for certain apparatus. Experience and better load conditions have changed this to a maximum rating which has become possible largely through the growth in the size of stations and systems.

The speeds of engine-driven units, both gas and steam, have become nearly standardized, and turbine-driven sets are rapidly approaching the same condition. With waterwheel units, however, the situation is such that the capacity and speed of the generator is often determined largely by the hydraulic conditions and the characteristics of the waterwheel which is to be used.

With steam engines the point of maximum efficiency is rather marked, as shown in the curve of Fig. 2, and the ratings are

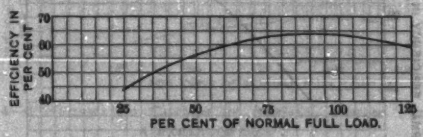


FIG. 2—PERFORMANCE CURVE OF 8000-H.P. COMPOUND CONDENSING STEAM ENGINE.

usually such that the engine is working under its most economical load at the rating of the electrical generator. With gas engines, however, the efficiency increases with the load, beyond the capacity of the engine, as shown in Fig. 3, and for this reason the rating of the engine is generally made as nearly as possible to its maximum capacity, leaving a small margin for regulating purposes. With the steam turbine, Fig. 4, the efficiency curve is usually so flat that it is a question of desirable overload capacity which limits the rating of the turbine.

In the waterwheel unit, the efficiency usually falls off rapidly above and below the maximum point, so that the rating of the generator should correspond to the point of maximum efficiency of the waterwheel. Steam engines and steam turbines are designed to operate with certain variations both in pressure of the steam and conditions of vacuum. Gas engines must accommodate themselves to variation in the quality of the gas.

With the waterwheels, however, by far the large majority of installations are subject to a change in head which varies over a wide percentage. In many of the low-head installations the back water may bring about a change in head which is beyond the capacity of one wheel to accommodate, and in some plants additional wheels must be mounted on the same shaft and cut into service at times of low head. One particular instance of this kind is the plant of the Chattanooga and Tennessee River Power Company, where the head may vary from 20 to 42 ft. (6.1 to 12.8 m.). In most of the large developments this change in head is the limiting feature in the design of the waterwheel as related to the generator capacity, for in all electrical work it is necessary that the speed of the generator be kept constant.

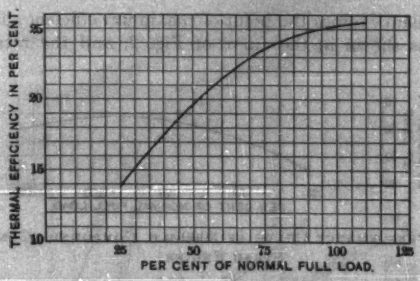


FIG. 3—PERFORMANCE CURVE OF 2000-H.P. GAS ENGINE

Waterwheel runners of different designs are compared on the basis of their specific speeds. The specific speed of a waterwheel is the number of revolutions per minute at the point of maximum efficiency that a similar wheel will give when it delivers one horse power under one meter head. By comparison of the specific speeds we can judge of the characteristics of waterwheel runners without respect to their actual speed, power or head. A high specific speed means a high actual speed, and a low specific speed means a low actual speed in revolutions per minute. For this reason waterwheels with low specific speeds are generally used with high heads in order to make the speed of the generator within the range of good electrical design.

Waterwheels with high specific speeds have very deep runner vanes, and these are liable to erosion under high heads; also,

the efficiency curves of runners of high specific speed are more pointed than with the low specific speed type, and this allows a narrower margin for operation under the best conditions. This is clearly shown in curves in Fig. 5.

The maximum full-load capacity of a turbine is that point beyond which the output decreases with an increase in gate opening. The margin between the point of maximum efficiency and of maximum capacity depends upon the specific speed of the runner, and is smaller the higher the specific speed. This is illustrated in Fig. 5, which shows that as the specific speed is increased, the point at which maximum efficiency occurs approaches nearer to the power delivered at full gate opening. The specific speed may thus be increased to such an extent that the point of maximum efficiency and maximum output coincide. With low heads and high specific speeds it is therefore desirable

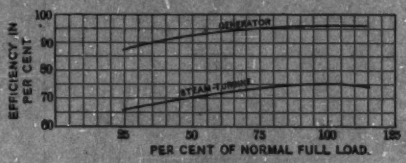


FIG. 4—PERFORMANCE CURVES OF 5000-KV. STEAM TURBO-GENERATOR SET

to operate wheels near their point of maximum output, and to obtain the best results, the generator should be designed giving consideration to this point.

Referring again to the curves in Fig. 5, it will be noted that the full-load capacity occurs at about 6 per cent above normal or rated full load in all three cases. This is in accordance with the general practise, the margin being allowed for governing. It is also noted that for curves *B* and *C* the efficiency is falling off very rapidly at 6 per cent overload, and that should the gate be opened still further the output would reduce instead of increase. If, with low specific speed wheels, as represented by curve *A*, the gates were still further opened, the power would continue to increase to some extent.

The point of maximum efficiency for wheels represented by curve *A* occurs at about 90 per cent of normal full load, in the case of *B* at 93.5 per cent, while in the case of *C* the maximum

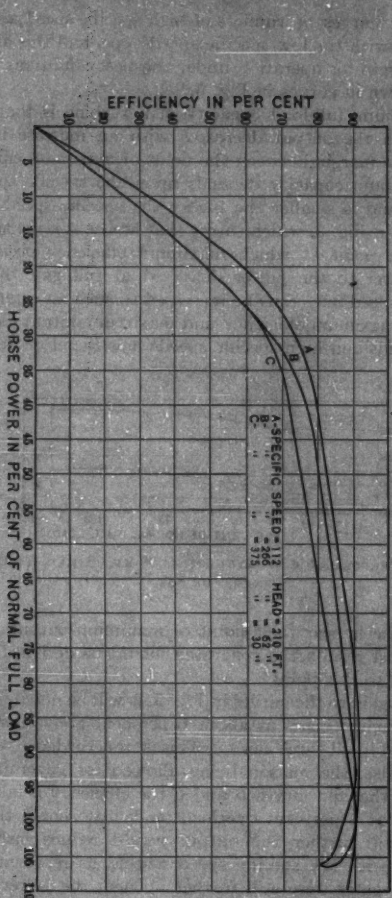


FIG. 5—PERFORMANCE CURVES OF SEVERAL TURBINES FOR VARIOUS HEADS AND SPECIFIC SPEEDS AS SHOWN

efficiency occurs just at the point of normal or rated full load. Thus, as stated before, the power at which the maximum efficiency occurs approaches nearer to full load as the specific speed increases.

With high-head wheels, as represented by curve *A*, the efficiency remains very high over a very large range in power, while for low-head wheels, curve *C*, the efficiency falls off rapidly as the power is reduced below the normal full load. For this reason it is desirable to run low-head wheels under practically full load conditions. With high-head wheels this is not so important, as the efficiency is still high at partial loads. With wheels as represented by curve *C*, it is also necessary to allow some margin above the normal full load for governing, as it is desirable to operate the turbine at its point of maximum efficiency. With high-head wheels, curve *A*, such a margin need not be allowed.

The curves plotted in Fig. 5 represent operating conditions under constant head. This, however, is not always realized, especially in low-head plants where floods and dry seasons sometimes cause quite a variation in the head, and this has, as previously mentioned, quite a bearing on the selection of the waterwheel, and should therefore be given careful consideration.

If the speed of the unit could be allowed to vary at all times as the square root of the ratio of the heads, the shape of the performance curve for any head other than normal would be the same as that secured at normal head, but the output would vary as the 3/2 power of the ratio of the heads. In the case of wheels driving alternating-current generators a speed variation is not permissible and the speed must be kept constant, irrespective of any variation in head which may occur.

In Fig. 6 is plotted a set of curves illustrating the effect of a varying head. A 10,000-h.p. turbine is assumed to operate normally under a 32-ft. (9.75-m.) head, the speed to be constant for a range of heads from 26 to 38 ft. (7.92 to 11.6 m.). As the head goes up to 38 ft. (11.6 m.) the shape of the curve approaches more closely curve *B* in Fig. 5, while when the head falls to 26 ft. (7.92 m.), the speed being constant, it approaches more closely to curve *C*. In other words, when operating under a 38-ft. (11.6-m.) head, the speed is lower than the best speed for the runner under that head, while when operating under the 26-ft. (7.92-m.) head, the speed of the wheel is higher than the best speed. Under 38 ft. (11.6 m.) head the point of maximum

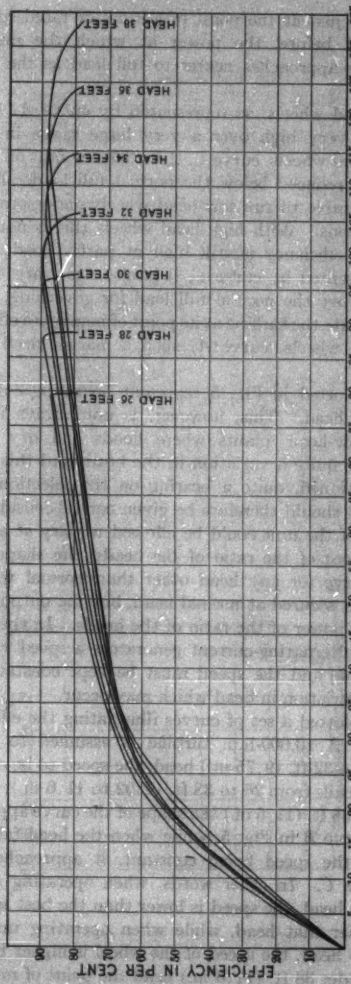


FIG. 6—10,000-H.P. TURBINE CURVES SHOWING EFFICIENCY AND POWER FOR CONSTANT SPEED AND A NORMAL HEAD OF 32 FT. FOR VARIOUS HEADS AS SHOWN

efficiency is, furthermore, considerably below the normal full load at that head, while under 26 ft. (7.92 m.) head the power at which maximum efficiency occurs is the actual full load, illustrating the points discussed above in reference to the relation of the power at which maximum efficiency occurs and the normal full-load power for various specific speeds.

Let us assume that a selection of a wheel is to be made for an installation, and that performance curves are desired, showing the expected efficiency for various loads and speeds. Curves *A*, *B* and *C* in Fig. 5 may each represent a possible curve, dependent upon the revolutions selected for the turbine in question, the revolutions being directly proportional to the specific speeds, and they will illustrate the manner in which the efficiencies at partial gate openings will fall off in any one

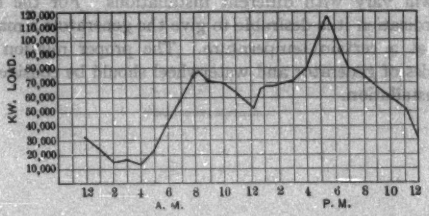


FIG. 7—TYPICAL LOAD CURVE OF LARGE CENTRAL STATION—DECEMBER LOAD

case, depending upon the actual revolutions per minute selected for the design of the wheel. They will also give an idea as to the margin between the normal full load and the power at which the point of maximum efficiency will occur. In the selection of a speed for any installation, therefore, aside from the cost of the generators, the question of the wheel efficiencies at partial gate openings has a considerable bearing. Where a unit is likely to operate under a very wide range in power, it would be advisable to select a wheel represented by curve *A*, giving a high efficiency for a considerable range in power.

All power systems have a more or less varying load, and this has a very important bearing on the selection of the proper generating equipment and on the economy of the plant. The load will vary considerably, not only during the 24 hours of the

day, but also for different periods during the year. The load curve also differs materially for different kinds of load, such as for central stations, industrial establishments, street railways, etc.; a typical load curve of a central station is represented in Fig. 7.

The size and capacity of the units in a hydroelectric station is determined, in many cases, quite largely by the hydraulic conditions. In operating, the number should, wherever possible, never be less than four, unless the station forms part of a larger system. It is better to operate machines as near full load as possible, and to start new units instead of utilizing overload capacities. Where sudden overloads of considerable magnitude come on the system for very short periods it is, of course, necessary to have a wheel capacity sufficient to care for them.

The foregoing discussion indicates that waterwheel characteristics will vary with different installations. For the sake of standardization it is desirable to give the generators a maximum rating at a certain temperature. The proper relation of the capacities of generator and waterwheel should be considered for each installation.

GROUP IV PAPERS

(Pages 731 to 804)

Miscellaneous Subjects Relating to Rating

(a) OIL SWITCHES

Rating of Oil Circuit Breakers with Reference to Rupturing Capacity, by G. A. Burnham.

(b) SPARK GAP

The Sphere Spark Gap, by S. W. Farnsworth and C. Fortescue.

The Calibration of the Sphere Gap Voltmeter, by L. W. Chubb and C. Fortescue.

(c) WAVE FORM

Potential Waves of A-C. Generators, by W. J. Foster.

Wave Form Distortions and Their Effects on Electrical Apparatus, by P. M. Lincoln.

A Proposed Wave Shape Standard, by Cassius M. Davis.

(d) REGULATION

The Experimental Determination of the Regulation of Alternators, by A. B. Field.

Regulation of Definite Pole Alternators, by Soren H. Mortensen.

Generator and Prime Mover Capacities, by David B. Rushmore and E. A. Lof.

DISCUSSION ON GROUP IV PAPERS—[(*a*) OIL SWITCHES, (*b*) SPARK GAP, (*c*) WAVE FORM, (*d*) REGULATION]. NEW YORK, FEBRUARY 28, 1913.

Paul M. Lincoln: The paper of Mr. Burnham's on oil circuit breakers opens up an interesting subject. The question of the method of rating an oil circuit breaker is an important one, and is one upon which the Standards Committee, I believe, should take some action. I am prepared to accept most of the suggestions made in Mr. Burnham's paper. It is necessary to rate circuit breakers in various ways; one way to rate them is in regard to their current-carrying capacity, and they must have such a rating. They must also have a voltage rating to indicate the maximum voltage of the circuit upon which they may be used.

These two ratings, however, do not fix the ability of a given breaker to *protect*, and it is this ability to *protect* that is of foremost interest to the operating man. It seems to me that the best method of giving such a rating is the one which is suggested in this paper, namely, the kilovolt-ampere capacity which a circuit breaker will be guaranteed to interrupt. Now, the kv-a. capacity which the breaker will interrupt successfully will depend almost entirely upon what is back of the breaker. Of course, it stands to reason that the breaker which has a small power plant back of it will not be called upon to interrupt as much as one which has a large power plant back of it. Moreover, the amount of power which the breaker is called upon to interrupt will depend not only on the size of the power plant back of it, but also on the character of the generators, and particularly on the question whether or not there are current-limiting devices placed in those generators or in other portions of the circuit, so as to limit the amount of power which the breaker is called upon to interrupt. In these days when there is such a tendency to use current-limiting devices either in generating circuits or feeder circuits, or between the sections of busbars, the method of rating breakers suggested in the paper becomes, in my opinion, the logical one. It is not logical to rate a breaker with regard to the amount of synchronous apparatus that is back of it, because a given breaker may be protected by reactance in series with it, so that the amount of power which it is called upon to interrupt is not a function of the total plant back of it, but an amount limited by the current-limiting devices. It seems to me logical therefore to rate breakers for the kv-a. capacity which the breaker will be guaranteed to interrupt.

M. G. Lloyd: I ask if there is any limitation on what happens to the breaker when it ruptures the circuit?

Paul M. Lincoln: Of course, good practise must place a limitation on that, but just what that good practise is, has not been definitely determined. It is the practise of a number of

operating companies at present to overhaul breaker contacts, after they have been called upon to interrupt short circuits, and the practise in the past has indicated that such an inspection is essential to the continuity of service. Such inspections, of course, are necessary only when the breaker is called upon to act at somewhere near its ultimate breaking capacity. In ordinary conditions, a breaker may not show the slightest signs of inconvenience or distress, but when the breaker is used at such capacities as tend to push it to the limit, there may be some throwing of oil or burning of contacts, which it is wise to investigate, before the breaker is put back into service.

M. G. Lloyd: I do not think that quite answers the point as regards the rating in the rules. How much overhauling would be permissible for deciding that the breaker had been overrated?

Paul M. Lincoln: I do not know that the rules could go so far as to make any definite determination of that point. I am not prepared, at least, to suggest any reading of the rule which covers that point.

F. D. Newbury: I do not think it is a matter for the rules to be explicit upon, and I think that, as long as the damage to the breaker has not been greater than can be remedied by replacement of the contact the breaker has not been overrated.

A Member: The author has called attention to the complexity of the problem of rating circuit breakers, and the difficulty of expressing that rating is something that can be readily understood. Because of this difficulty many of the manufacturers have paid no attention whatever to the rating of the switches they buy. That may sound like a confession, if it was taken for what it is worth. Our company pays very little attention to the guarantee of the manufacturer, depending on a knowledge gained of the switches by testing and experience. The reason for that is this—the rating at present, as the author has indicated, is unsatisfactory. The amount of energy that is back of the switch is the determining factor as to what will happen to the switch when it is called upon to do extreme work, that is, opening a short circuit. It is put on a device and an automatic arrangement is put on the switch, so that it will open the short circuit when called upon. The extreme condition that it is called upon to meet is a short circuit directly back of the switch. What will happen to the switch will depend entirely on the available energy back of the switch. Just what volume of current the switch will open cannot be determined, and you cannot tell whether it will come up to specifications, as we have not a micrometer in the short circuit when it opens. We do not know what it is called upon to do and we do not know whether it meets specifications or not. It seems to me that a far better rating would be the kv-a. capacity that would be ruptured, not the currents passing through the switch, but the kv-a. back of the switch, under which conditions the switch may open

sufficiently to protect the circuit—switches would be rated in certain values—instead of certain ampere values of continuous capacity, they would be rated to protect a circuit having back of it certain available instantaneous energy. Suppose they are rated for 100,000 kv-a., or any capacity that the manufacturer sees fit; that will be more good to the operating engineer than a kv-a. rating he knows he can never find out whether the switch is meeting or not.

Paul M. Lincoln: The man who installs a plant, who fixes the size of the choke coils, etc., is the man who can determine how much current a given switch will be called on to interrupt as a maximum. The manufacturer cannot determine that. If the manufacturer will say that such a switch will protect 10,000 amperes on a 100,000-volt line, and if you go beyond that you are taking chances, that is as much as the manufacturer can do. The man who installs it and applies the limiting devices is the man who can determine the maximum the switch will be called upon to rupture under the worst conditions. It seems to me that when a manufacturer has said that a given switch is good for rupturing so many kv-a. on such and such a voltage line, he has gone as far as he can. The amount of instantaneous kv-a. which the switch is called upon to rupture is not only a function of the current-limiting devices in series with it, but also a function of the time-limit which is placed on the breaker. It is well known that if you allow a breaker to stay in for several seconds after the short circuit has come, so that the instantaneous rush of current is over, and the generators have settled down to somewhere near their normal condition, the stress on the breaker will be less severe than if it is called upon to rupture instantly.

A Member: Apparently I did not make myself clear, because my position is exactly the same as Mr. Lincoln's. We both agree absolutely. One point of my suggestion is this—that if it were stated in terms of the available energy back of it, the same thing as stating the capacity, you call the attention of the engineer to the fact that he must figure it from that side, and not figure on what is going to happen on the other side of the switch, the apparatus it protects. At the present time the rating leads the mind of the average engineer to the amount of energy that is behind the switch rather than the energy that can be pumped into it.

Ford W. Harris (by letter): The suggestion to rate breakers by the maximum current they can safely open is not a new one, being one of those more or less obvious thoughts that occur to a considerable number of people at different times. It has to my certain knowledge been several times suggested to at least one manufacturer and on every such occasion has been finally rejected as undesirable.

In the first place it involves complications that are not at first sight evident. For example, the influence of phase relation

of the voltage and current at the instant of rupture is very marked in limiting the value of this current. If the voltage wave at the instant the current reverses is near its maximum this current is much more likely to reverse than if the voltage wave is at a low value. It would probably not be sufficient to give a single maximum value, but in addition it would be necessary to state exactly how this value would be modified by the characteristics of the circuit as to inductance and capacity.

Then this safe maximum current would represent the current that would produce a failure of the breaker, divided by a factor of safety. We have, however, no accurate measure of the failure point. At a certain current the breaker will start to throw oil, and as the severity of the short circuit is increased it will throw oil, burn contacts, and produce other mechanical distortions in a greater degree. At just what point shall we apply our factor of safety? If this rating is to be a definite one, some agreement on this point will be necessary.

In the same way it would be necessary to come to some agreement as to what the factors of safety should be and how they should be modified by enclosure which prevents the breakers enclosed from being regarded as so much of a life and fire hazard.

Even if the rating were adopted I am not at all sure that it would be of any considerable engineering value, due to the difficulty of determining in advance just what current to expect at certain points and in general the impossibility of waiting until tests can be made before specifying the breakers. While there are in this country certain men who can figure what this current will be and while there exist data that could make this calculation feasible to the average engineer, these data have been obtained at a very considerable expense and it is very doubtful if those who have them would care to make them public.

Considered commercially, I cannot see where this rating would be of any very considerable value. The average purchaser would rather have a blanket guarantee, that the breakers he is purchasing will take care of conditions in the applications that he can define to the manufacturer, than to have a partial guarantee that the breakers will open a certain current. Indeed, it is very doubtful if the purchaser would be willing to dispense with the broader guarantee even if the current were defined.

In other words, it seems to me that this matter of circuit breaker ratings is a much more complicated matter than has evidently been assumed, and that the rating proposed is not likely to be of any very considerable value either to the purchaser or to the manufacturer.

Chester Lichtenberg (by letter): The rating of an oil circuit breaker, unlike that of most other electrical apparatus, must be given in terms both of the normal and abnormal circuit conditions under which it is intended to operate. Its complete rating requires, therefore, an enumeration of the following properties:

1. Continuous current-carrying capacity.

2. Maximum circuit pressure capacity.
3. Maximum energy-dissipating capacity.

The continuous current-carrying capacity of an oil circuit breaker is the maximum current at any given frequency which its parts will carry continuously without exceeding a specified temperature rise. This will depend primarily on the design of the device and the materials used in constructing it, and also upon the temperature and configuration of the leads connected to its terminals and the quality of this connection. The latter points are very important, and in making tests of oil circuit breakers, great care must be exercised to have the temperature of the leads not in excess of that of the oil circuit breaker terminals. In general, the maximum temperature of any part of an oil circuit breaker should not exceed 35 deg. cent. above an average room temperature of 25 deg. cent., but in no case should the maximum temperature of the oil exceed 75 deg. cent.

The maximum circuit pressure capacity, commonly known as rated voltage of an oil circuit breaker, is the maximum equivalent pressure of the circuit to which it may be safely connected. This rating depends on the design of the device, the pressure rises which may occur on the circuit in which it is connected, and the desired factor of safety. On most circuits operating at 45,000 volts and below, it is admissible to give the pressure rating of the oil circuit breaker in terms of the circuit pressure. Above this point, however, and in some special cases below it, it has been found advisable to follow the practise adopted by insulator manufacturers, and give the pressure rating of the oil circuit breaker in terms of the maximum pressure it will withstand for a short interval of time such as 30 or 60 seconds, and the pressure under which it can operate continuously. The ratio between these two ratings varies from 1.5 to 10, depending on the circuit conditions and the degree of safety specified.

The maximum energy-dissipating capacity, generally known as the rupturing capacity, of an oil circuit breaker, is the maximum amount of energy which the device can dissipate when interrupting a circuit of given voltage and frequency. This factor of the rating is by far the most difficult to determine and fix, as it depends on a large number of independent variables of design and circuit conditions. It can only be determined experimentally with considerable difficulty and within wide limits which require exact definition.

It is, therefore, suggested that the Standards Committee consider a method of rating oil circuit breakers which will include the following:

1. A current rating based on temperature rise.
2. A pressure rating based on ordinary circuit pressure rises together with a reasonable factor of safety.
3. An energy-dissipating rating based on the maximum current which the device can safely interrupt on a circuit of given pressure and frequency at the least favorable power factor, without showing any external signs of distress.

It is also suggested that:

1. The maximum temperature rise on any part of an oil circuit breaker should be limited to 35 deg. cent. above an average room temperature of 25 deg. cent., but in no case should any maximum temperature exceed 75 deg. cent.

2. Oil circuit breakers for use on circuits between 2500 and 45,000 volts shall be able to withstand a high-pressure test between live parts and ground of three times rated pressure for 30 seconds.

3. Oil circuit breakers for use on circuits exceeding 45,000 volts shall be able to withstand a high-pressure test between live parts and ground of 2½ times rated pressure for 30 seconds.

4. The safe rupturing capacity of an oil circuit breaker shall be the maximum equivalent current which the device can interrupt at rated pressure and frequency at the least favorable power factor without showing signs of distress, and shall be given in amperes at rated pressure and frequency.

5. The maximum rupturing capacity of an oil circuit breaker shall be the maximum equivalent current in amperes which the device can interrupt without being destroyed and shall be given in amperes at rated pressure and frequency.

F. W. Peek, Jr.: In the discussion of the interesting paper of Messrs. Chubb and Fortescue on their development of the sphere gap voltmeter it may be of interest to state our experience, and add data which we have obtained in this work.

The needle gap has long been a useful means of approximating high voltages; with the present extra high voltages, however, we have about outgrown it. Although it is possible to measure high voltages with a fair degree of accuracy with the needle gap, too much skill is required, and too many variables must be considered, especially at extra high voltages. The voltmeter coil offers a reliable means of high-voltage measurement, but a gap method is often desirable because the gap measures the maximum point of the wave and this is what determines the breakdown of insulation. With a gap method it is thus not necessary to take oscillograms, except to know that the wave fairly approximates the sine: that is, is a good commercial wave. The sphere gap used within the limits described below seems the best solution of the practical problem. It is free from the eccentricities of the needle gap, requires less skill in manipulation, the space factor is small and, furthermore, the curve can be readily calculated within small percentage error. There is one variable that must affect all gap measurements—air density. Over the ordinary range of temperature and variation of barometer *at or near sea level* correction may be made by multiplying by δ, where

$$\delta = \frac{3.92\, b}{273+t}$$

For high altitudes, where the range of δ is large, the correction

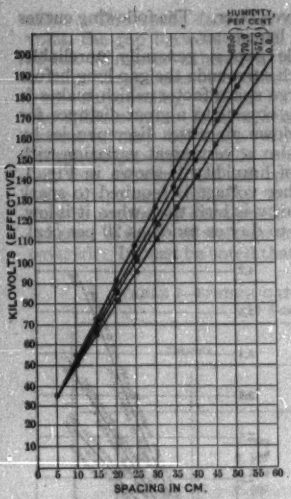


FIG. 1—NEEDLE-GAP CURVES FOR DIFFERENT RELATIVE HUMIDITIES.

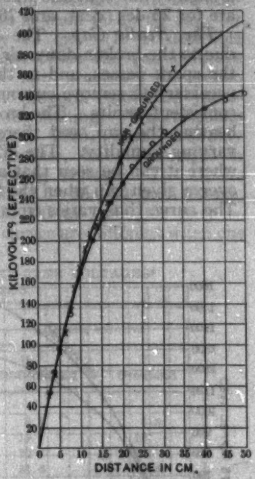


FIG. 3—SPARK-OVER CURVE, 25-CM. (DIAMETER) SPHERES.

Drawn curve, calculated; points, measured values.

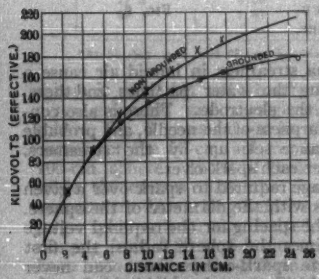


FIG. 2—SPARK-OVER CURVES, 12.5-CM. (DIAMETER) SPHERES.

Drawn curves, calculated; points, measured values.

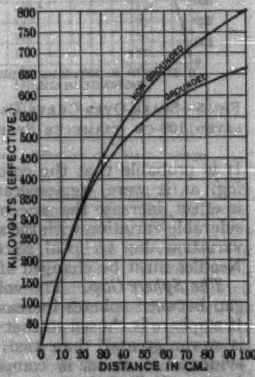


FIG. 4—SPARK-OVER CURVES (CALCULATED) 50-CM. (DIAMETER) SPHERES.

is slightly different and will be given later. The following curves are for 25 deg. cent. and 76 cm. barometer.

The Needle Gap. The needle gap is generally unreliable, due to the broken-down air which surrounds the gap long before the spark passes, and to the large space factor which makes it necessary to remove surrounding objects to a great distance for consistent results. The broken-down air causes discrepancies by heating the gap, and there is also a very great variation with varying humidity. The effect of humidity is shown in Fig. 1, where it can be seen that a higher voltage is required to spark over a given gap when the humidity is high than when it is low. The curve thus varies from day to day as much as 20 per cent.

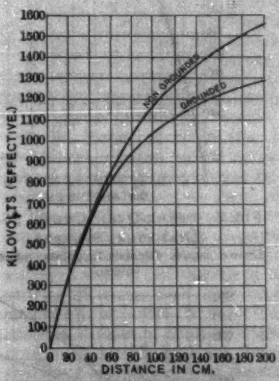


FIG. 5—SPARK-OVER CURVE (CALCULATED) 100-CM. (DIAMETER) SPHERES.

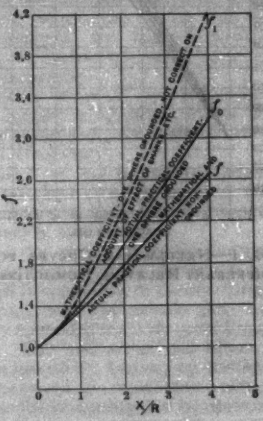


FIG. 6

It is probable that the corona streamers in humid air cause a fog, as it were, agglomerating the water particles, and these, in effect, increase the size of the electrode. There is also considerable variation with the sharpness of the needle, and probable variation due to local resonance set up by the streamers. Needles must be changed after each spark-over.

The Sphere Gap. The voltage required to spark over a given gap between spheres increases with the diameter of the sphere. If a sphere is chosen so that the spacing for the required voltage is never greater than two times the sphere radius, the first evidence of stress is complete spark-over, corona can never form, and all of the undesirable effects and variables due to the broken-down air are eliminated. Humidity has no measurable

effect The space factor is small—for instance, at 200 kilovolts, the gap between needle points is from 50 to 60 cm., for 25-cm. diameter spheres it is only 13 cm. (It is desirable to have the spheres or needles at least twice the gap distance from surrounding objects.) It is not necessary to polish the spheres after each spark-over. Several thousand measurements may be made without repolishing. Discrepancies in sphere-gap tests made years ago, 1895, were probably not due to condition of sphere surface, but to changes in wave-shape and difficulty in measuring voltage. The curves may be accurately calculated. With 12.5-, 25-, 50- and 100-cm. spheres, a range of voltage from 20,000 to 1,500,000 may be covered. It must be noted that the curves are different when one

TABLE I—SPHERE GAP SPARK-OVER VOLTAGES*
12.5-CM. SPHERES

Spacing		Kilovolts effective	
Cm.	In.	Non-Grounded	Grounded
0.25	0.098	6.5	6.5
0.50	0.197	12	12
1	0.394	22	22
1.5	0.591	31.5	31.5
2	0.787	41	41
3	1.181	59	59
4	1.575	76	75
5	1.969	91	89
6	2.362	105	102
7	2.756	118	112
8	3.150	130	120
9	3.543	141	128
10	3.937	151	135
12	4.72	167	147
15	5.91	188	160
17.5	6.88	201	168
20	7.87	213	174

*At 25 deg. cent. and 76 cm. barometer. Effective sine wave voltage.

sphere is grounded and when both spheres are insulated. Fig. 2 gives grounded and non-grounded curves for the 12.5-cm. sphere, Fig. 3 gives curves for the 25-cm. sphere, Fig. 4 gives curves for the 50-cm. sphere, and Fig. 5 gives curves for the 100-cm. sphere. In all of these the drawn curve is calculated, while the crosses mark the measured values. The calculated curves were drawn long before measurements were made on the larger spheres, from laws derived from a series of tests on spheres ranging from 0.32 to 5.0 cm. in diameter. No measurements have been made on the 100-cm. sphere, but the calculated curve, Fig. 5, should be correct within a small percentage. Measured values are given in Tables I, II and III. Practical range for different diameters is given in Table IV.

TABLE II—SPHERE GAP SPARK-OVER VOLTAGES*
25-CM SPHERES

Spacing		Kilovolts effective	
Cm.	In.	Non-Grounded	Grounded
0.5	0.197	11	11
1	0.394	22	22
1.5	0.591	32	32
2	0.787	42	42
2.5	0.983	52	52
3	1.181	61	61
4	1.575	78	78
5	1.969	96	94
6	2.362	112	110
7.5	2.953	135	132
10	3.937	171	166
12.5	4.92	203	196
15	5.91	230	220
17.5	6.88	255	238
20	7.87	278	254
22.5	8.85	297	268
25	9.83	314	280
30	11.81	339	300
40	15.75	385	325

TABLE III—SPHERE GAP SPARK-OVER VOLTAGES*
50-CM. SPHERES

Spacing		Kilovolts effective
Cm.	In.	Grounded value
2	0.787	40
4	1.575	76
6	2.362	112
8	3.150	145
10	3.937	185
12	4.72	220
14	5.50	250
16	6.28	275
18	7.07	300
20	7.87	320
22	8.65	345

*At 25 deg. cent. and 76 cm. barometer.
Effective sine wave voltage.

TABLE IV

Diameter cm.	Grounded Effective kv.† range	Non-grounded Effective kv.† range
12.5	50–170	50–200
25	50–320	50–375
50	50–600	50–725
1000	50–1200	50–1400

† Sea level—spacing not exceeding 3R.

A curve on the 12.5-cm. sphere was made up to 25,000 volts at 1000 cycles and coincided with the 60-cycle curve. At 50,000 cycles similar curves were made on spheres and needles. The sphere gap curve for this frequency was somewhat lower than the 60-cycle curve, while the needle gap curve was very much lower. If a needle gap is set so as to just spark over when a steep wave-front or high-frequency voltage of constant value is applied, and a sphere gap is similarly set, and these two gaps are then placed in parallel, and the same impulse voltage applied, apparent discrepancy results. Spark-over will take place across one gap, and not the other, even when the spacing on the non-sparking gap is decreased. This will be noticed in all cases where electrodes of different shape are employed in multiple. The reason, apparently, is that energy is necessary to start rupture in the dielectric, the amount of energy varying with the shape of the electrode. This introduces a very small time element, which differs for different gaps. The effect, however, is rarely

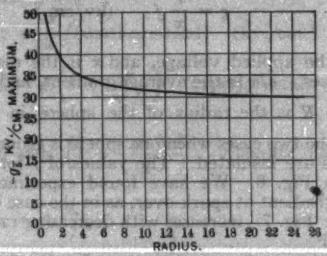


FIG. 7

noticed in commercial voltage waves, as any variation in the wave shape, in commercial waves, is not sufficiently abrupt, or is slow compared to the time lag. Naturally, as the time lag is very short, it can not be measured by the oscillograph or any other instrument with mechanically moving parts. It has been studied by comparing spark distances of different electrodes in parallel. The effect is important in lightning arrester gaps, where the protecting gap should have a smaller time lag than the protected apparatus—that is, the protecting gap must discharge before the apparatus breaks down.

In making arc-over tests, as, for instance, on insulators, the effective transformer ratio should first be calibrated by sphere gaps. The arc-over test should then be made with sphere gaps out of the circuit and voltage determined by the calibrated ratio curve. Care should be taken that the same generator and the same method of voltage control be used in the arc-over test as in the calibration test.

Method of Measurement. Up to 200,000 volts, measurement was made by a voltmeter coil giving a great degree of accuracy. Check was made on this by step-down transformer, by ratio and by corona starting point, results from which were all in agreement. Above 200,000 volts, step-down transformer and ratio were used. The voltage ratio was very close to turn ratio. A good wave, very nearly sinusoidal, was used, and oscillograms were taken for correction in low side of transformer, in voltmeter coil and in step-down transformer. The waves on high and low sides were practically the same.

Water tube resistances were used in series with the gap, limiting the arc current to from 0.25 to 1.00 ampere. The potentiometer method[1] of voltage control was used.

Calculation of Curves. The voltage gradient on the air is greatest at the sphere surface. This stress or gradient derived mathematically is expressed[2]

$$g = \frac{e}{x} f \qquad \text{(kv/cm.)}$$

where e is the applied voltage, and x is the distance between sphere surfaces. e/x is the average gradient, and f is a function of $\frac{x}{R}$, where R is the radius of the sphere in cm. The f is different in the two cases when one sphere is grounded, and when both spheres are insulated. The values of f for the two cases are given in Fig. 6. We have found experimentally that g_s, the surface gradient at spark-over, as in the case of g_s for corona on wires (see Fig. 7), increases with decreasing radius. It may be expressed[3]

$$g_s = g_0 \left(1 + \frac{a}{\sqrt{R}}\right).$$

g_s for a given size of sphere is constant for the practical range of spacing used in measuring, that is, when x is not less than about $0.5\sqrt{R}$, not greater than $3R$. When x is less than $0.5\sqrt{R}$, g_s increases very rapidly, because the spacing is then less than the "rupturing energy distance."[4] At very small spacings, gradients as high as 200 kv. per cm. are required for rupture. The "rupturing energy" has been calculated for wires.[4]

The increased value of g_s when x is large, seems to be only apparent and due to the shank, surrounding objects, etc., better distributing the flux or lessening the flux density. When

1. See *The Law of Corona and the Dielectric Strength of Air*, by F. W. Peek, Jr., TRANSACTIONS A. I. E. E., 1911, XXX, p. 1889.

2. Mathematical values of f have been derived by Russel, *Philosophical Magazine*, vol. XI, 1906.

3. The constants are approximately $g_0 = 27.2$ $a = 0.54$.

4. See *The Law of Corona and Dielectric Strength of Air-II*, TRANSACTIONS A. I. E. E., 1912, Vol. XXXI, p. 1051.

both spheres are insulated this effect is small and is inappreciable for large spheres, where the mathematical f may be used. When one sphere is grounded, however, this apparent increase of gradient is very great if the mathematical f_1, which does not take account of surrounding objects, is used. The f values given in Fig. 6 are for the *non-grounded case.* They are the *mathematical values* and, within the limits prescribed, *give a practically constant graded* g_s. The dotted line, Fig. 6, is the mathematical curve for the grounded case. This does not hold, due to the effect of shanks, etc., which it does not consider, and the actual curve is f_0. This was derived experimentally, assuming g_s constant. For a given value of $\frac{x}{R}$, f_0 is constant, independent of the size of the sphere (from tests on spheres from 0.32 to 25 cm.). Where x is greater than 2 R (practically 3 R) the expressions do not hold, because corona then forms before spark-over.

We have then

$$g = \frac{e}{x} f \text{ (mathematical)} \quad \text{(kv./cm.)}$$

$$g_s = g_0\left(1 + \frac{a}{\sqrt{R}}\right) \quad \text{(experimental) (kv./cm.)}$$

Therefore

$$e_s = g_0\left(1 + \frac{a}{\sqrt{R}}\right)\frac{X}{f} \quad \text{(kilovolts max.)}$$

or

$$e_s = g_s \frac{X}{f}$$

As an example of its use—

What is the spark-over voltage for 25-cm. spheres (one grounded) 20 cm. apart?

$$R = \frac{25}{2} = 12.5$$

$$x = 20$$

$$\frac{x}{R} = \frac{20}{12.5} = 1.60$$

$$g_s = g_0\left(1 + \frac{a}{\sqrt{R}}\right) = 31.2 \text{ kv./ cm. max.}$$

(See Fig. 7)

$$f_0 = 1.74 \text{ (from Fig. 6).}$$

$$e = g_s \frac{x}{f_0} = 362 \text{ kv. (max.)}$$

$$e = \frac{362}{1.41} = 256 \text{ kv. (effective)}$$

For small spheres the range of the constant part of the g_s curve is very small, as the effect of shanks extends over a greater range. Hence, in practise, the above expression is especially applicable to spheres 10 cm. in diameter and above.

In order that the sphere gap may be used at various altitudes, and corrections made, curves must be taken at various air densities. The full correction will be made as in the case of parallel wires:

$$g_s = \delta g_0 \left(1 + \frac{a}{\phi(\delta)\sqrt{R}}\right.$$

This is being investigated. The constants of these equations will be given when the data are more fully worked up.

C. E. Skinner: Those of us who have had to deal with the old needle gap in the years gone by know all the trials and tribulations through which we have had to go in trying to get accurate measurements of voltages higher than 50,000. In listening to the discussion of the various papers that have been offered here in the last three days, we have all noted the differences and the difficulties which have come up, and the problems which have been put up to the Sub-committee on Revision of Standards. Here is a case where it would appear that the work done could be accepted without change, and probably with little or no criticism. The use of the sphere gap for something like two years in a practical way has shown its adaptability and its convenience, its accuracy for all kinds of conditions, and the calibration, by different observers and by different methods, is very close. I think the Institute and the Standards Committee are to be congratulated on one set of papers, which ought not to require much further testing or question.

I might incidentally mention that one of the greatest difficulties encountered in connection with the sphere gap is the manufacture of the spheres themselves, as the manufacture of accurate spheres of the sizes which are required for these gaps is no easy matter.

J. A. Sandford, Jr.: There is one decided advantage, I think, in the use of the sphere gap as compared with the needle gap, which was not mentioned either by the authors of the paper or by Mr. Peek, to any one who has a large number of measurements to make by the use of the spark gap. I refer to being able to take measurements with the voltage on the test piece, and moving the gap from a wide separation up to the point where the spark jumps. If I am not mistaken, the sphere gap will give accurate readings under those conditions, and on this point I would like to have Mr. Farnsworth and Mr. Fortescue corroborate what I say. I think we will at once realize what this means. It simply means we need take only one reading in each case to establish what the voltage is at that particular instant; this in contrast to the large number of readings necessary to determine the test

voltage when using the method described by Mr. Peek in the A.I.E.E. TRANSACTIONS for 1912, page 908. Of course, naturally, as in all other work, it requires several readings in order to get a fair average, but with the needle point spark gap I think it is quite well known that if the voltage is applied to the test piece with a wide separation of the points, however carefully as you may bring the points together, it will be found that the readings will vary greatly, and at least there will be some difficulty in getting accurate results. I feel that this one advantage alone has probably saved me at least 75 or 80 per cent of the time I have to use in tests of this kind.

Comfort A. Adams: May I ask those who have used this method what percentage of accuracy it is reasonable to expect in the use of the sphere gaps by men such as are ordinarily called upon to make routine tests of this sort in manufacturing establishments?

L. W. Chubb: In answer to Prof. Adams's question in regard to the accuracy reasonable to expect with the sphere gap, I will say that we believe that variations depend entirely upon the steadiness of the circuit, transformer, and switching apparatus. We believe that the true accuracy of the gap is within a very small part of one per cent. If a spark passes, the potential difference between spheres has reached a very definite voltage, and after the spark has passed, any further rise of potential between the spheres is practically prevented.

On a steady circuit below 100 kv-a., if the gap is opened beyond the breakdown and slowly closed, the results have been found to check within less than 0.05 cm. At higher voltage, when little jumps of corona in the high-tension circuit are apt to produce surging, or on unsteady circuits, repeated determinations may vary considerably, but such variation is not chargeable to the sphere gap.

If you will refer to the curves in the paper you can see with what precision the points fall upon the (envelope) curve drawn.

S. W. Farnsworth: In answer to Mr. Sanford's, question, we can say that the method of measuring a given voltage by moving the spheres together until breakdown occurs is a reliable one.

The paper which we presented, purposely avoids entering into a theoretical discussion on the breakdown voltage between two equal spheres, for this has been well covered by others. We do not feel that we are the first who have considered using spheres for a spark gap, but, so far as we know, we are the first in this country who have used large spheres for the high voltages which we are daily using, and the results which we have obtained have been so satisfactory that we feel the manufacturers will be benefited by having spheres adopted as a standard in place of the present needle-gap standard. It may be well to quote from an article by Mr. J. Lustgarten on "High-Tension Porcelain Line Insulators," which appeared in the July,

1912, number of the *Journal of the Institution of Electrical Engineers:*

"With regard to the spark gap, there is a tendency to measure voltage by the needle-point spark-gap standardized by the American Institute of Electrical Engineers. Those who have worked with the gap specified, know that it is difficult to check the American values and even to repeat their own results on successive days. One reason for this lies in the effects on the brush discharge of humidity, pressure and temperature, position of the needles with respect to the supports and neighboring objects, and the local conditions of the circuit. The brush discharge in the case of needle-points always precedes the spark (excepting at very small distances). A screening by metallic disks at the back of the needles will not prevent humidity, pressure and temperature destroying the standard gap. The author uses spheres, the diameters being chosen so that no brush discharge, or rather, no glow, will be observed at the sparking voltage. Thus all sparking voltages are below the uncertain kink stage in spark-distance curves, the kink being due to the formation of the brush discharge. The effect of humidity is eliminated. The effect of temperature can be corrected, the spark potential varying inversely as the absolute temperature. Variations in atmospheric pressure affect the spark potential less before the brush stage than after. Weicker gives the correction for spark potentials for a 10-mm. variation in pressure from 735 mm., as 1.36 per cent. Up to 70 kv. (r.m.s. values) 2-cm. diameter spheres are suitable, to 125 kv. 5 cm., and to 200 kv. 10 cm."

This article gives the opinion which an English experimenter holds of our present needle-gap and the proposed sphere gap.

Messrs. Chubb and Fortescue in their calibration of the proposed gaps, have not dealt with the effects of humidity, temperature and pressure, and while it may be advisable to investigate with respect to these, it hardly seems necessary in view of the great quantity of evidence already available.

The article by Weicker which was referred to in the quotation above, is the most complete investigation of the general subject of sparking voltages that has come to our attention. It is to be found in the "Mitteilungen ueber Forschungsarbeiten auf dem Gebiete des Ingenieurwesens," Berlin, 1911, No. 100, pp. 1-48.

His investigations bear out the results obtained by others, and it can be stated that, for the sphere spark-gap used over a separation not greater than the diameter of the spheres, the influence of the factors of humidity, temperature, pressure, frequency and electrode capacity on the sparking voltage is as follows:

Humidity—No effect.

Temperature—The sparking voltage is inversely proportional to the absolute temperature.

Pressure—The sparking voltage is directly proportional to barometric pressure.

Frequency—Within the range of commercial frequencies, namely, 20 to 75 cycles, frequency has no effect on the sparking voltage.

Electrode capacity—So far as we know, Weicker is the only one who has investigated the effect of electrode capacity, particularly, and he states that it has no influence on the sparking voltage.

Comfort A. Adams: May I ask again in regard to the frequency? It is stated that it was between 60 and 70 cycles. Was the investigation carried beyond this range, and is there any difference between a flat-topped e.m.f. wave and a very peaked e.m.f. wave?

L. W. Chubb: The frequency range for our work was from 25 to 70 cycles. The results were independent of frequency as far as we could judge. The results expressed in terms of maximum voltage were also found to be independent of wave-shape through a rather wide range of voltage distortion. I believe that it can be shown both experimentally and theoretically that the break is dependent upon only the maximum potential between spheres, and independent of frequency even as high as one million cycles, provided the spheres are working below the corona point.

Oscillograph tests were made with some very peaked waves at 100 kv. and directly on the high-voltage circuit. The records showed that the break came at the peak of the wave, as closely as could be measured.

Voltage across the gap was recorded on the film. No change could be found in the cycles preceding the break. The voltage dropped quickly to zero when the break came, and by comparison with the previous cycle it was evident that this drop started at the maximum point. Such is not the case when the needle gap or other electrodes are used above the corona point and in series with resistance. There is quite a disturbance due to the streamers before the break.

I agree with Mr. Peek that it requires a certain amount of time for the spark to take place, but I believe that with the spheres it will take place if the voltage reaches the critical point and drops at a rate corresponding to the peak of a million-cycle wave. Certainly the unstable point has been reached and the electrostatic charge of the spheres can flow through the spark just as quickly as it can flow back into the circuit. Such would not be the case with the progressive discharge of the needle gap, as the electrostatic charge would be expended in ionizing the air near the electrodes.

Percy H. Thomas: It seems to me with this sphere gap we have made quite a distinct advance in the measurement of alternating-current voltages. I want to suggest two thoughts; the first is this: In view of the relatively high capacity of the

gap itself, on account of the spherical form of terminal, compared to the needle-point terminals, a certain material charging current will flow to the terminals. If series resistance is used, as is usually the case with the gap, we cannot rely on the gap to take account of disturbances of all frequencies, because the resistance will cause a drop on high frequency on account of the charging current of the spheres. For waves of 60 cycles, or 120 or 133 cycles, undoubtedly resistances can be introduced so small as not at all to interfere with the accuracy of the method, but with frequencies of 10,000 cycles or 100,000 cycles, I should say it would be necessary to be very careful to see that no resistance in series with the gap terminals was vitiating the results.

One result of this condition is to cut out from the gap the effect of any accidental oscillations of very high frequency that may be superimposed on the alternating voltage, and if in testing a transformer, some little spark from the terminal somewhere sets up an oscillation, with spark-gap needle points, that oscillation will make the needle-points break down. With the sphere gap, using a large series resistance, I should expect the gap would not show these little superimposed high-frequency oscillations.

The second thought I wish to offer is that the sphere gaps can not always be safely used, except without series resistances, for determining the maximum voltage on high-frequency experiments, and even without series resistance, it could be used only where its capacity is small in regard to the capacity of the apparatus which is being tested.

I want to take this opportunity to ask Mr. Peek some questions, with regard to the actual time required for the breakdown of an air-gap. Suppose we apply instantly, a voltage to an air-gap four times as great as the voltage necessary to break it down, I would like to know if Mr. Peek can tell us how long it will take for the first flow of current to occur across the gap, assuming there is no inductance in the system other than the discharge gap.

I would like also to have some statement of the experimental evidence on which the conclusion is based that there is a time-lag in the breakdown of an air gap.

This is a very important and a very interesting matter, and it is a thing which keeps coming up—this matter of the lag of the spark gap at breakdown, and it is put forward as the explanation of a great many of our high-frequency phenomena. Personally I am open-minded on the subject. I have not been convinced, by any of the experiments I have so far seen or heard reported, of the existence of this lag as a material factor, and yet I am not sure that there is not such a thing. Are we not justified in concluding that, if there is a lag in the breakdown of an air-gap, it is only material for extremely high frequencies, less than a millionth of a second? Take, for example, the famous surges of Hertz, with Maxwellian electromagnetic waves. Hertz

explored with a small circle of wire having a small air-gap in it, and his discharge apparatus, if I am not mistaken, was small and of very high frequency. He had sparks across a small air-gap. If his air-gap must necessarily have considerable time to break down, it could not break down on frequencies the alternations of which are less than the time of breakdown, because the mechanical force on the electron will alter in direction with the alteration of the applied e.m.f. The air-gap was able to break down on the frequencies Hertz used, which were very, very high, and if this logic is sound, the range of spark lag must be much less than a million cycles per second.

Paul M. Lincoln: The gaps which Hertz used in his experiments were extremely minute. I do not remember just what they were, but they were of the order of a few thousandths of an inch at the most, as I recall. As I see it, this breakdown of the air is a progressive action; particles of the air next to the terminals become ionized and they, by collision, ionize other particles. That means, if I am correct, that the time of breakdown of the air-gap is a function of its length, so that the air-gap which Hertz used would break down many, many times quicker than the air-gaps described, for instance, in the paper read by Mr. Thomas in December.

C. Fortescue: In the first place, the condition of breakdown through the insulator is entirely different from the condition of breakdown between two large spheres that are separated a distance less than their diameter. We might compare the operation of the small sphere or an insulator and the operation of the two large spheres which are separated less than their diameter, to the operation of an ordinary trigger of a gun and the operation of a hair trigger; the sphere gap being represented by the hair trigger. The very instant that the intensity at the surface of the sphere reaches a certain point the breakdown occurs. No energy is required to complete the rupture outside of that already stored in the electric field between the spheres. The distance the spark has to travel is a minimum, and the action is like that of a hair trigger.

Mr. Thomas makes mention of the lagging of the spark. It may be safely said that the sphere gap is, in that respect, infinitely superior to any other method of measuring the maximum voltage that has yet been suggested. In the case of the needle spark-gap, in order to produce breakdown, all the air surrounding the points has to be ionized. This means that there is an energy component in the e.m.f. between the points and the edge of the corona which not only produces a lag of the actual e.m.f. at the point of breakdown but also causes a change in the wave form of the e.m.f. between the edges of the corona from that between the points. Thus in the needle spark-gap there is no doubt quite an appreciable lag for very high frequencies, but with the sphere spark-gaps as we have recommended them, I think that the lag, if such does exist, is extremely small.

As far as the small spheres are concerned, they produce just about the same action as needle-gaps. Wherever there is corona at breakdown there is bound to be a lag, because there must be enough energy in the oscillation to produce the corona before breakdown can take place, and where the energy has to be stored in the field there must necessarily be a time lag of the e.m.f. at the points of rupture. This is entirely eliminated where large spheres are used because then we have a condition of breakdown without corona.

M. W. Franklin: I do not happen to call to mind now any definite researches bearing on the matter of the time required for the formation of a spark, and therefore I can only speak from a sort of integrated activity in reading and following such papers for the last ten or fifteen years. As I remember it, it is a definite, experimental fact that there is a time element in the formation of a spark, even in the case of a spark between two spheres, and that time must, I think, be reckoned in millionths of a second at the utmost.

Furthermore, in regard to the suggestion that Mr. Thomas made, it does not at all follow that it requires even a millionth of a second for a spark to break down, that that spark gap cannot break down at ten million cycles. If you only consider that there may be a dozen cycles of e.m.f., each one causing a to and fro surging of the two electrons which happen to lie in the body, and that to and fro surging creates more electrons, until there is a cumulative effect, you can see that such a thing is possible from a half dozen cycles of enormously high frequency, and I do not think it possible to argue, because the spark gap breaks down at 10,000,000 cycles, therefore the time lag must be less than a ten-millionth of a second. I am quite firmly of this opinion, not from a theoretical point of view, but merely as a result of having read nearly everything that has been published on the subject of discharge through gases during the last fifteen years, and I am sure Mr. Peek and those who have been working on the subject are justified in thinking of a time-lag as existing. I am quite sure, also, that that time must be extremely small, in the neighborhood, no doubt, of millionths of a second, but I am also quite sure that the criterion suggested by Mr. Thomas would not be a proper criterion, even for forming an estimate of the extent of that time lag.

Charles P. Steinmetz: A few years ago Mr. Hayden and myself made some rather extensive investigations on the disruptive strength of air between spheres and needles, using impulses. The results of these investigations show a time lag, which was startlingly large, and measured not by microseconds, but by milliseconds, under the conditions of the experiments. Our conclusions, however, were that, (at least under our test conditions), it was not so much a time lag, as an energy lag; that the breakdown is not a question of time but a question of energy and that the time lag may vary with the rate of energy supplied, and be variable at the disruptive point.

That puts an entirely different phase on the question of high frequency. You may have millions of cycles and still no appreciable time lag, because as each successive half wave subsides, the next half wave continues. So it is quite likely that the phenomenon which we call the time lag, and which has been more or less elusively indicated in very numerous tests and observations, is merely the result of the obvious fact that it requires energy to break down air, and that energy must be supplied, and that the breakdown, therefore, must be compared to the amount of time necessary to bring that energy to the point of disruption.

That leads us, however, to some interesting conclusions. At the spark-gap between needle-points, the corona or brush discharge which appears is very extensive and affects an enormous volume of air. The amount of energy which is absorbed by the brush discharge is enormously large, very many times greater than the energy of electrostatic charge of large spheres, and experience seems to show that the time lag in discharging at very high voltages between needle points is very many times greater, and that the energy of the current flowing into the needle points before the discharge, is also very much greater, than the energy or current absorbed by large spheres, and that also explains the superiority of spheres, provided they are used at such voltages as do not occasion corona. Under these conditions no energy is absorbed in the gradual breaking through of the air. On the contrary, energy is statically stored in the spheres, and is available to puncture the air.

As regards our recent discovery that spheres are really better than needle-points, you must realize that that applies only within a certain range of voltage. Probably for low voltages, up to 20,000, the needle-gap will remain the standard, because the sphere gap at these low voltages is so small as to be inaccurate, owing to the fact that any arcing at the surface of that sphere, which is negligible in its effect at distances corresponding to 100,000 volts, is fatal and entirely changes the disruptive voltage when you come to 2000 or 3000 volts.

That explains why in those early days where the range up to 20,000 volts covered practically the entire important field of high voltages, when you carefully studied the relative advantages of the needle-gap and sphere gap in the early 90's, the general consensus of opinion was that the needle-gap was the only one which could be considered, because it was definite and was of a length which is measurable, ranging from 5 mm. to 20 mm. But that very advantage becomes a fatal disadvantage when you are dealing with a half million volts or more, and the needle-gap becomes many feet in length. You then have to build a specially large structure to accommodate the spark-gap, and you have to dissipate so much energy in the corona, before you get a discharge, that it requires very large apparatus, very large time lag, and a smaller energy oscillation which is not observable at all. It is merely a question of the relative value of voltages,

whether the sphere-gap or needle-gap is preferable. At lower voltages we do not recommend changing from the needle-gap to the sphere-gap, but when you come to voltages of such magnitude that the sphere gap is a measurable length, then the sphere gap is the more reliable and the more workable method.

C. Fortescue: I think that Dr. Steinmetz has summed up the attitude of those who have recommended the spark-gap very thoroughly. There are one or two points in this spark-gap paper of ours that I want to call attention to. We say: "The effects of atmospheric pressure and humidity have also had only a negligible effect on the break-down voltage." I want to correct that statement and say that what we meant was this: that during the time we made the tests the change in temperature and atmospheric pressure was too small to produce an appreciable effect.

I would like to say a few words in regard to Mr. Layman's experiment some years ago in which he found those discrepancies. I think the discrepancies were due to the fact that the spheres were so good; in other words, oscillations which take place in any commercial circuit will break down the sphere-gap, where they might not break down the needle-gap, and I think that is probably the cause of his discrepancies. We found when we had a circuit that was kept very steady, and carefully observed, that all the points were consistent throughout, but we happened to work part of the time on a circuit on which some cranes were operating, and every time a crane started or stopped it produced a surge which would break down the spark-gap, and that was noted time and again, and pointed plainly to the fact that the slow surge set up by the starting current of the crane caused an oscillation which, at the peak of the wave, produced a superimposed ripple which broke down the spark-gap.

C. E. Skinner: I want to add that the very fact that the sphere gap does break down, due to these surges, is a distinct advantage in its use for measuring voltages where we are dealing with insulation, because it is these same surges which break down the insulation.

Percy H. Thomas: I think that Dr. Steinmetz has put this thing in pretty nearly its true light. It does require energy to cause a discharge through air, but it seems to me reasonable if we can apply the requisite amount of energy in a very short time, no matter how short, we can get the discharge in that time. Taking that point of view, we have only to consider how much energy has to be put in and how quickly it can be supplied. As Dr. Steinmetz pointed out, the electrostatic charge on the sphere-gap does supply stored energy very close to the break-down point, and is thus able to maintain a difference of potential rigidly at that point.

The amount of energy which it takes to start a discharge through the air, will I think, be found to be very small. The discharge is started by the velocity produced in the electrons,

and it does not take much time to start the cumulative liberation of more electrons. Furthermore, the time that it takes to produce such motion must be extremely minute, since these very light bodies have to move only a very short distance.

L. W. Chubb: Dr. Steinmetz has mentioned his experiments made to find out whether a single impulse of voltage would break the same air gap as a continuously applied voltage. The authors conclude that the break is a function of time, but I believe that the maximum peak of the impulse voltage was the true variable. I would like to ask Dr. Steinmetz whether this impulse voltage could not have been very much in error due to the flux lag, eddy currents in the core, and leakage reactance, in such a transient test.

Charles P. Steinmetz: I think I can explain that this phenomenon could not have been present, because whatever magnetic effect eddy currents in the iron can exert, would be exerted on the primary and secondary of the transformer simultaneously. The counter e.m.f. appears instantly in the direct-current primary supply by the closing of the switch, and therefore it must have appeared instantly in the case of the secondary. The only source of error which might exist would be the distributed capacity of the secondary winding, and that can be calculated, but in these particular transformers we measured the distributed capacity, at least the magnitude of it, and so knew in which condition of test that effect was negligible; that is to say, negligible within the errors of test, a matter of 10 per cent, more or less.

Since that time we have repeated some of our tests and have taken an oscillogram of these waves, that is, these single impulses, and we employed so much more energy that you can, in the oscillograms, see the effect of the initial rapid rising and tapering of the impulses. We checked up that phenomenon, and while there is some error, the error is of very small magnitude indeed.

L. W. Chubb: I would also like to ask Dr. Steinmetz whether the sparking distances and size of terminal were such that they worked above the corona point?

Charles P. Steinmetz: Most of them were above the corona point. Some of them, those with spheres, were below the corona point. At that time, which was before the investigation of corona made with Mr. Peek, we did not specially register that, but my impression is that in previous cases we did observe marked corona, and previous to that we arranged the curve of sparking distances between the spheres, so it appears that at the circumferential condition, with very sharp and marked break in the characteristic of the disruptive strength curve, which is observable, that in the case of the sphere gap at that point the corona begins. I think corona has a material time-lag resulting from its energy-lag, but that phenomenon requires still further investigation. We have started some investigations trying to study this form of corona, but have not proceeded far enough yet to arrive at any satisfactory results.

J. B. Whitehead (by letter): There will be little dissent from the opinion of the authors that the needle-point air gap as at present described by the A.I.E.E. Standardization Rules is an inconsistent and unsatisfactory standard for voltage measurement. In support, however, of that much abused apparatus it may be pointed out that the standardization rules have apparently not taken proper account of the best information and study of the needle gap as a means of measurement of voltage. The instrument has been studied somewhat extensively by W. Weicker and his results published in the *Electrotech. Zeitschrift* in 1911. Without in the least advocating the needle gap as a standard, it may be pointed out that it has now been shown that the needle gap gives widely varying results below 60,000 volts, but that above that figure under uniform external conditions the results are very constant, provided the angles of the points are chosen between 20 deg. and 100 deg. Sewing needles, therefore, if used in the spark gap introduce a source of error which it would be fairly easy to remove by stipulating a wider angle for the point.

The use of the sphere gap was suggested by Alexander Russell in 1907 as a satisfactory arrangement for testing dielectric strength. In an earlier paper, referred to by the present authors, he attempted to reduce the formulas of Kirchhoff for evaluating the electric intensity between the spheres. In this way he aimed to present ready methods for calculating the voltage at which a given sphere gap would break down.

He also worked out a number of cases from the simpler though still somewhat unwieldy expressions and presented them in the form of a table for reference. Subsequently Russell's discussion and results were attacked by de Kowalski and Rappel in an article in the *Philosophical Magazine* for 1909, in which they presented a number of careful measurements with alternating voltages. They used spheres up to 30 cm. diameter but did not carry the width of gap above 2 cm. Russell has presented two other papers dealing with the sphere gap to the Physical Society of London, which have been presented in the Proceedings of that Society for 1911. The result of the discussion so far is that there is considerable doubt as to whether the electrical intensity within the sphere gap may be accurately calculated and the fact that measurements of different observers show a rather wide discrepancy.

The authors have not in my opinion strengthened the case for the sphere gap. They have made an important contribution to the experimental knowledge of this instrument, but their paper hardly presents a sufficiency of data to warrant the claim that the sphere gap should be used as a standard of measurement. I wish to express my interest and admiration for the ingenious method they have adopted for deriving the maximum value of voltage.

In offering my few criticisms I trust that the authors will realize that they are due only to my conviction that the sphere

gap presents almost, if not quite, the same limitations as the spark gap. First, while admitting possible influences of pressure, temperature and moisture, the authors present no data showing the magnitude of the influence or the absence of influence of any one of them. Second, the influence of proximity of extraneous objects is granted by the authors and suggestion made of various screens and future measurements to study this influence. Third, little if any statement is made of the degree of accuracy with which the observations may be repeated. In fact in this connection the single values as given in the tables show discrepancies in many cases of an order of magnitude of from 1.5 to 2.5 per cent; *e.g.* with the 25-cm. spheres for the gaps of 4 cm. and 11 cm., for the 37.5-cm. spheres the gap at 5 cm., and with the 50-cm. spheres the gaps at 8 cm. and 12 cm. have been selected without any close scrutiny of these tables. Although the range in which the authors' observations coincides with those of de Kowalski and Rappel is very narrow, there is a considerable discrepancy in the values obtained.; *e.g.* for gaps of 1.35 and 1.23 cm. and 30-cm. spheres the results of the latter experimenters show 37.5 and 34.6 kilovolts respectively. The present authors also fail to interpret the symbols at the tops of their tables. It would be interesting also to know by what method they arrive at the figures of electric intensity as given in Fig. 4.

The principal objection to both the needle gap and the sphere gap in my opinion lies in the fact that they do not take advantage directly of natural constants. It has been amply shown now that the electric strength of air depends markedly on the distribution of electric intensity in relation to the volume of air. For this reason it has heretofore proved impossible to present a certain method for calculating length of a needle or sphere gap to break down at a definite value of voltage. On the other hand, the use of the appearance of corona on the interior of two concentric cylinders obeys a law upon which close agreement now obtains among many observers. The influences of pressure, temperature, moisture have also been studied with resulting good agreement. It is therefore possible to write down at once the dimensions of a concentric-cylinder measuring apparatus which under given conditions of temperature and pressure will develop breakdown at the surface of the inner conductor at a given voltage. The objections to this method are the difficulties of observing the point at which corona starts, and the necessity of changing the inside cylinder for different voltages. The first of these objections is not a serious one and it is my hope soon to present to the Institute a paper describing the adaptation of the above principle as a means of measuring voltage. For over two months daily observations have shown a consistency under widely varying atmospheric conditions to within less than 1 per cent.

F. M. Farmer and E. D. Doyle (by letter): This proposal to measure the deviation of the wave form of an alternator from a

pure sine wave by means of condenser reactance appears to be so simple and practical that one wonders why it has not been suggested before. The present Institute standard is indeed unsatisfactory, as it not only does not penalize the harmonics in proportion to their undesirability but is cumbersome and expensive to apply.

The reason for using a large inductive reactance to determine the standard value is not apparent. It would obviously seem

TABLE I

(a) Measurements on a badly distorted wave *without* voltage transformers.

Test No.	Capacity microfarads	E.m.f. volts	Current milliamperes	Distortion ratio
Ammeter—Weston 7.5 volt dynamometer type voltmeter No. 3201. Resistance 55 ohms, inductance 19 millihenries.				
1	1.959_2	107.2	8.13	1.02_6
2	1.007	122.9	8.0	1.71_3
3	1.007	114.8	9.04	2.07_3
4	1.007	129.4	11.47	2.33_5
Ammeter—Weston 7.5 volt dynamometer type voltmeter No. 6776. Resistance 93 ohms, inductance 19 millihenries.				
1	1.007	107.0	41.4	1.01_3
2	0.603_3	122.1	47.4	1.70_4
3	0.603_3	114.5	53.9	2.07_0
4	0.603_3	129.4	69.1	2.34_4
Ammeter—Weston soft iron type milliammeter No. 435, 74 milliamperes. Resistance 101 ohms, inductance 292 millihenries.				
1	1.007	106.7	42.8	1.05_8
2	0.454_1	122.1	40.7	1.94_8
3	0.454_1	144.5	65.1	3.32
4	0.454_1	128.7	74.6	3.38_3
(b) Measurements on a badly distorted wave with voltage transformers.				
Voltage stepped up and stepped down with two 6600-110 volt, 200-watt voltage transformers. Ammeter, Weston voltmeter No. 6776.				
1	0.603_3	105.2	24.3	1.01_4
2	0.603_3	120.6	46.9	1.70_8
3	0.603_3	112.3	53.2	2.08_2
4	0.603_3	126.1	67.4	2.34_2
Voltage stepped up and stepped down with two 2200-110 volt, 50-watt voltage transformers. Ammeter, Weston voltmeter No. 6776.				
1	1.007	109.0	42.1	1.01_7
2	0.603_3	123.9	48.1	1.70_7
3	0.603_3	117.1	55.8	2.09_5
4	0.603_3	130.4	70.1	2.36_3

Test No. 1, fundamental only, (60 cycles).
Test No. 2, fundamental with 53.5 per cent third harmonic.
Test No. 3, fundamental with 37.5 per cent fifth harmonic.
Test No. 4, fundamental with 53.5 per cent third harmonic and 37.7 per cent fifth harmonic.

more simple to use a condenser of known capacity, in which case the sine wave reactance is of course simply $X_s = \frac{1}{C\omega}$. The distortion ratio would be obtained by the simple measurement of the condenser reactance on the distorted wave.

As the convenience of the application of any new standard is of great importance, it occurred to the writers that some figures taken in actual measurements would be of value, since Mr.

Davis has not given any figures indicating the magnitude of the quantities with which he had to deal in obtaining the values that he gives in his paper. Furthermore, two questions arise in the application of this method which made it desirable to make some tests. First, is it practicable, in order to avoid the use of large condensers, to use ammeters of small range without introducing too much resistance and inductance in series with the condenser? Second, can the distortion of high-voltage machines be measured by using small capacity (voltage) transformers?

TABLE II

(a) Measurements on a moderately distorted wave without voltage transformers. Current measured with Weston voltmeter No. 6776.

Test No.	Capacity microfarads	E.m.f. volts	Current milliamperes	Distortion ratios: By calculation*	Distortion ratios: By measurement
1	1.007	119.5	47.5	1.04_3	1.04_4
2	1.007	118.7	51.4	1.11_2	1.13_4
3	1.007	120.2	53.5	1.15_2	1.17_4

(b) Measurements on a moderately distorted wave with voltage transformers. Current measured with Weston voltmeter No. 6776.

Test No.	Capacity microfarads	E.m.f. volts	Current milliamperes	Distortion ratios: By calculation*	Distortion ratios: By measurement
Voltage stepped up and down with two 2200-110-volt, 50-watt, voltage transformers.					
1	1.007	116.4	46.4	1.04_2	1.04_4
2	1.007	116.4	50.3	1.11_3	1.13_3
3	1.007	116.8	52.1	1.15_2	1.17_2

Test No. 1, fundamental with 10.2 per cent third harmonic.
Test No. 2, fundamental with 10.2 per cent fifth harmonic.
Test No. 3, fundamental with 10.2 per cent third harmonic and 10.2 per cent fifth harmonic.

NOTE: "Calculated" values of distortion ratio obtained as follows:
For fundamental wave $R = 1.00$ by definition.
For distorted wave,

$$R = \sqrt{\frac{E_1^2 + (3E_3)^2 + (5E_5)^2}{E_1^2 + E_3^2 + E_5^2}}$$

where E_1, E_3, E_5 are mean effective voltages of fundamental, third harmonic and fifth harmonic respectively.

* Sine wave assumed. Oscillograph tests of the charging current of a condenser showed that the fundamental is not a perfect sine.

Tables I and II show results of tests made at the Electrical Testing Laboratories with various distorted, waves with and without voltage transformers. A high-grade subdivided mica condenser was used and the current was measured with different types of ammeters.

These results lead to the following conclusions:

1. As is to be expected, milliammeters of the soft iron vane type have too much inductance. The inductive reactance becomes appreciable, so that the voltage across the condenser is no longer

equal to the generator voltage. Therefore, in order to use an ammeter of this type it should not be less than 250 milliamperes in range and suitable indications on such an instrument would require about 10 or 12 microfarads capacity at 25 cycles.

2. Voltage transformers of as small as 50 watts capacity can be used for stepping down the voltage without introducing an objectionable error.

3. All that appears to be necessary to obtain the distortion ratio of any machine as defined in the proposed definition is a standardized subdivided mica condenser of one or two microfarads capacity, a 100-milliampere ammeter with low inductance such as a dynamometer or hot wire instrument, a voltmeter of any standard type, a standard voltage transformer and a speed counter. The condenser should obviously be a high-grade one in which the phase angle is within a very few minutes of 90 deg.

Charles P. Steinmetz: The purpose of Mr. Davis's paper is to recommend the establishment of a wave standard which shall be based on the distortion ratio; that is, on the ratio of the current taken by a condenser with the distorted wave and the current which the same condenser would take with a sine wave. Mr. Davis's paper also suggests a method of obtaining the distortion ratio, where the alternator is not accessible. This condition exists when you are considering a commercial circuit, as, for instance, in my laboratory. Under such circumstances it is not always practicable to determine the exact frequency. You can use the same wave with the same frequency, smoothing out the higher harmonics by high inductance. The natural way, where you have a generator available, would be to measure capacity with a condenser and have the capacity exactly known, and measure the current input at measured voltage, and also measure the frequency.

Naturally, what we are interested in is the voltage wave as it exists during all conditions of operation, not only at full load, but at no-load. Thus it would be very nice to standardize and specify that the voltage should be taken at no-load as well as at full load, and, more particularly, at condenser load, where the distortion is probably greatest. The only trouble is that we have already spent much time in the discussion of "equivalent" loads and it will be agreed that the subject presents grave difficulties. You see the importance of specifying a wave test at full non-inductive load and at full condenser load, where we are discussing means of getting equivalent load tests and equivalent heat tests. Even though we may know the condition which we should desire, we cannot load the generator, because we do not have the power available. Zero power factor load naturally does not mean anything here, because while it may be leading current it is not a condenser load, and does not exaggerate the harmonics. Thus the only practical solution seems to consist in assuming that the different harmonics which appear under load, would probably be there at no-load, and would show the distortion ratio of the no-load wave. It might be exaggerated

at full load, especially condenser load, but we merely make allowance for that by specifying a low enough distortion ratio.

The fact is that the only additional harmonics which should appear under load are probably those resulting from the field distortion. Field distortion is the effect of non-inductive load. We do not much care for the harmonics, because a non-inductive load is equivalent to a resistance load, where the current follows the energy wave, and whatever distortion the voltage wave may have it would not have any serious effect. The case where harmonics are apt to be objectionable is mainly where the load is such as to exaggerate them, condenser load, and in that case the armature reaction is not distortional, but magnetizing, and therefore it is not practical to introduce additional harmonics. We thus see that we can get from the no-load test some good indication of the wave shape which we will need in practise. This appears to be the only test which is practically feasible.

B. G. Lamme: Mr. Foster's paper shows a great number of wave forms of different generators. Apparently one object of the paper is to show what variations seem to be permissible in good practise. It is a fact that many alternators working today without any trouble whatever, have what appear to be very bad wave forms. It is only in special cases that wave forms give any particular trouble, and sometimes the cause of the trouble does not really lie in the machine itself, but the bad wave form in connection with external conditions may result in disturbances in the system.

It is an old, well-known fact that any symmetrical wave form can be split up into a fundamental and harmonics of the odd order. A wave form obtained by means of the oscillograph may show us by analysis what harmonic is sufficiently large to cause disturbance, but it does not show us how to eliminate the harmonic. There are some suggestions in Mr. Foster's paper as to how this can be done by distributing the windings differently, or by differently shaping the poles. However, shaping the poles by blindly cutting off what one thinks should cure the trouble, is a dangerous proceeding, as this might result in exaggerating the very harmonic that it is desired to eliminate. In order to shape the poles to obtain the desired result, it is necessary to predetermine the diagram representing the field flux distribution, that is, the field form; and from the study of this and its relations to the e.m.f. wave, one can determine pretty definitely just what change is necessary to eliminate any particular harmonic.

I note that Mr. Foster mentions a hunting tooth to eliminate harmonics. I wish to call attention, however, to the fact that with a polyphase machine, one should be careful in using a hunting tooth, or an exact symmetry of phases will not be obtained. In three-phase machines, three hunting teeth should be used in order to obtain symmetry. One hunting tooth will not give the desired result.

A. E. Kennelly: In regard to Mr. Davis's paper, the plan presented therein seems to be a great advance over that offered in the existing Institute rule for determining wave form. The existing rule calls for determining the wave shape, then determining the corresponding equivalent wave shape, superimposing the two and measuring the greatest difference. That is a tedious operation which involves a considerable amount of personal equation. This proposed plan seems much more definite, more easily accomplished, and much more simple. It is, however, as has been before suggested by Dr. Steinmetz, a little indefinite in that it calls for the measurement of reactance in a condenser, and that suggests measuring the length of a bar, by measuring the volume of the cubical bulk whose side was the length of this bar. Would not it cover all the purposes Mr. Davis has in mind, if we were to define simply the distortion ratio of a voltage wave, as the ratio of the current produced by that voltage in a condenser to the current supplied in the same condenser from the sinusoidal e.m.f. of the same root-mean-square value? That definition would call for a standard condenser of specified dimensions, perhaps a standard frequency meter, a standard voltmeter, and a standard ammeter. By these instruments the measurements could be made without involving the definition of reactance in certain condensers.

M. G. Lloyd: Most of us are agreed that the present rule defining the limit of tolerance to departure from the sine form of wave is unsatisfactory, and Mr. Davis has given a possible substitute for it. All three papers point out that the present rule does not sufficiently penalize the higher harmonics under certain practical cases, such as the charging current on a transmission line. There are other cases, also, where the higher harmonics have greater importance than the rule gives to them, as, for instance, in eddy-current effects where they are large enough to make ripples in the flux wave. In other cases, however, it is not the higher harmonics which are most objectionable. In the case of hysteresis loss the lower harmonics are more detrimental than the higher harmonics, if compared on the basis of their equivalent value, as given by Mr. Davis's rule, that is, assuming them in inverse proportion to the order of the harmonic. It must be obvious then that in some cases this distortion-factor is a desirable criterion, while in other cases some other property of the wave is of greater importance, such as a form-factor; and in still other cases, perhaps an amplitude-factor or crest-factor.

While I am hardly ready to indorse the suggestion of Mr. Davis, it does seem better than the present rule. If the distortion-factor is to be made the measure of sinuosity, I should like to make the suggestion that the limit of tolerance suggested by Mr. Davis be cut down. I think he is entirely too liberal in defining what we shall accept as sufficiently close to a sine wave, or what may be called a conventional sine wave. To illustrate this I have computed the values in the accompanying

table, applying this limit of tolerance to the single case of hysteresis loss, such as would occur in the core of a transformer, since this is one of the practical cases to be considered in weighing the effect of departure of the wave from the sine shape.

In this table the percentage variation in hysteresis loss is given for the case of a single harmonic (a frequency three or five times that of the fundamental) for the two extreme cases where the phase angle is such as to produce the greatest increase and the greatest decrease in the wattage. The last column in the table gives the range in hysteresis values possible for the case of the third or fifth harmonic and the particular values of distortion ratio indicated.

CHANGE IN HYSTERESIS FOR THIRD AND FIFTH HARMONIC HAVING EXTREME VALUES OF PHASE ANGLES—FOR GIVEN DISTORTION RATIO

Distortion ratio	a	Order of harmonic	a/n	Increase in per cent	Decrease in per cent	Range in value possible, per cent
1.05	0.342	3	0.114	5.0	6.7	11.7
		5	0.068	1.6	2.6	4.2
1.10	0.493	3	0.1 4	6.5	10.8	17.3
		5	0.099	2.2	4.0	6.2
1.15	0.615	3	0.205	7.5	13.5	21.0
		5	0.123	2.7	5.3	8.0

It is seen from this table that if we allow a distortion ratio of 1.15 it is possible, with the third harmonic alone present, to have a hysteresis loss differing 13.5 per cent from the value with a sine wave, and in the case of the fifth harmonic the difference may be 5.3 per cent. The possible range in value is 21 per cent for the third harmonic, and eight per cent for the fifth harmonic. Even with a distortion ratio of only 1.10, the range for the third harmonic is 17.3 and for the fifth harmonic, 6.2.

The table illustrates that in the case of hysteresis it is the lower harmonics that are most objectionable, and it also illustrates, in my opinion, that the permissible allowance suggested by Mr. Davis is too great to come under the definition of a sine wave. If we should make a distortion ratio of 1.05 the limit of tolerance in a sine wave, it will be seen that the range in the value of hysteresis possible with a third harmonic is 11.7 per cent. It consequently seems desirable to me to limit the conventional sine wave to this value.

In adopting such a limit it is not a question of choosing a figure which will bring the best generators or other apparatus within the limit, for it is not necessary that a good machine be considered as giving an approximately sinusoidal wave. To

cut down the limit merely means that instead of being able to say that a certain generator gives a sine wave within the limits of the Standardization Rules we should have to say that it exceeds the limit by — per cent. The only reason I see given by Mr. Davis for such a wide latitude for distortion ratio is the fact that the average for 22 commercial alternators was 1.135. In my opinion the object in defining a sine wave should not be to make the average commercial alternator meet the definition.

While on three-phase circuits the third harmonic does not appear and the range in hysteresis value with the fifth harmonic would not be greater than eight per cent with a distortion ratio of 1.15, we should bear in mind that our definitions are not to be confined in use to the most common commercial conditions, but must be applicable to any case that may arise.

L. W. Chubb: Dr. Lloyd has covered about what I was going to say in regard to the low harmonics.

I think that it is a mistake to set a new standard of wave shape which penalizes the higher harmonics, in order to reduce transmission troubles, and disregards the low harmonic distortions which affect iron losses and in some cases prevent satisfactory parallel operation.

The paper starts with three objections to the present specification, which are not valid if the tester knows how to take wave-shapes and check them up according to the present specifications.

In answer to the first I would say that any maker of machines under a wave shape specification should have an oscillograph available. The oscillogram of the voltage wave can profitably be used for record, and to check the design, as well as to show that it meets the specification.

I object to the second objection because it is not necessary to measure any ordinates to obtain the equivalent sine wave. This I will show later.

I object to the third objection because no trial calculations are necessary to determine the position of minimum maximum deviation, nor is it necessary to plot any curves except to draw a circle of a certain diameter with ordinary compasses.

Suppose the wave shape in question is a polar curve. Its area which is proportional to the root-mean-square value can readily be measured with a planimeter and the equivalent sine represented by a circle of the same area. This circle, drawn on a piece of thin or transparent paper, should be placed over the polar curve of the wave in question and a needle should be driven through a point on the circumference of the circle placed over the pole of the other curve. The small piece of paper is then to be moved around the needle as a pivot until the minimum maximum deviation between the two curves measured on a radius vector is obtained. This difference, expressed in per cent of the diameter of the circle, is the final result.

The polar curve can be obtained by a special mechanical tracing table if the original record has been taken in rectangular

co-ordinates. But it is better to take the picture in polar form at once by revolving a celluloid disk film at synchronous speed in front of the slit of the oscillograph. The latter method, of course, eliminates the tracing operation, which is apt to introduce error.

The new wave shape standard proposed by Mr. Davis and the test method to be used give the designing engineer no idea of the resulting wave. All he will know is whether his machine meets a certain ratio. If his machine fails to show the specified ratio he will want to know why, and what can be done to reduce the harmonic distortions. If an oscillogram of the wave is taken, all of the necessary information can readily be obtained and a permanent record of the wave can be kept on file for future reference.

Mr. Lamme forgot to mention one source of quite serious harmonic distortion—that which is caused by the total flux pulsation in the machine.

If the number of teeth is divisible by the number of poles, there is a pulsation of the air gap reluctance under each pole, and as these pulsations will all be in phase, the total flux in the machine will pulsate, and cause decided ripples in the voltage wave. If the teeth per pole is an even number, this ripple will be composed of the odd harmonics next above and below this even component. In other cases it may be of tooth frequency or composed of the two odd components on each side of double tooth frequency.

Except for these tooth pulsations the wave shapes of machines can be quite accurately obtained from the designer's plot of the field form.

We find that the most satisfactory way to examine the wave shape of a generator is to take the oscillogram and find out not only how much distortion there is, but where the distortion is and what the cause is.

Oscillograms can profitably be taken and analyzed in all cases in which there is any question regarding the wave shape.

Good wave-shape design is a matter of evolution. Improvement comes from the study of the actual waves of the machines.

Accurate harmonic analysis can be made by taking the oscillogram on a disk film run at synchronous speed, printing it on a zinc disk, etching the line into the disk and placing this etched record on the table of a mechanical harmonic analyzer, and turning a crank. We have recently made up such apparatus and can analyze a wave in a few minutes, directly from the oscillogram and without any manual tracing.

The present specification does not sufficiently limit the high harmonics. The proposed standard will more than correct this fault, but allows too much latitude for the low-frequency components and takes no account of the phase relation of these low components.

This method of analysis is more applicable to the examination of wave shapes on finished machines, but can be applied in design,

before the machine is built, if the designer wishes to go to the trouble of analyzing his field form and adding this result trigonometrically according to his chording and winding. This latter method has not been found practical, but has some advantages over the method of predicting the wave shape by adding the field forms at a finite number of ordinates.

Comfort A. Adams: In regard to the pulsations of flux which have been mentioned, there are two varieties due to tooth variations of reluctance in the magnetic circuit. One affects the conductors in between the poles and puts kinks into the steep part of the wave. This does not affect the conductors under the center of the pole, or produce kinks in the peak of the wave. The other is a variation of flux distribution rather than a pulsation of flux in the whole magnetic circuit. It is sometimes called the flux swing, and affects the conductors under the center of the pole. It thus puts kinks into the peak of the wave. These two sets of kinks are of the same frequency and may both occur in the same machine, but they are not generally in the same phase, consequently it may appear, in counting the kinks in a wave, that you have an even number of kinks, but in analyzing these you will find that they actually produce odd harmonics in the theoretical sense of the term. The reason for this is that each set of kinks constitutes a tapering even harmonic which when analyzed gives two odd harmonics, one of the next higher order and one of the next lower order.

However, as Mr. Lamme has said, in the vast majority of turbo-alternators, as well as in many other machines, the air-gap is so long in proportion to the slot opening, that these pulsations are not appreciable.

Also, if it is desired to eliminate this effect, it is a simple matter to do so, by having a fractional number of teeth per pole. It has been shown in Mr. Foster's paper that such a change actually eliminates the harmonics in question.

The reason for this is very simple, namely, that in this case the several conductor belts of a given phase are not located in exactly the same position with respect to the poles under which they happen to be at the instant under consideration. It can be easily shown that a fractional number of slots per pole per phase is equivalent to a much larger number of slots per pole per phase as far as the wave shape is concerned, *e.g.*, $1\frac{1}{4}$ slots per pole per phase is practically equivalent to 5 slots per pole per phase, $4\frac{1}{4}$ to 17 and so on. It is thus a simple matter to wipe out all tooth kinks, even when the gap is short and the available number of slots small.

Mr. Chubb has pointed out a method of computing the harmonics of the e.m.f. wave from the analysis of the flux distribution curve. Much time may be saved in this method by making use of carefully computed tables which will be found in a paper* which I read before the Institute on the subject of *Electromotive Force Wave-Shape in Alternators*, nearly four years ago.

*A. I. E. E. TRANS., XXVII II, p. 1053.

It would seem therefore that there is little excuse for building alternators which do not conform more closely to the sine wave than suggested by Mr. Davis. On the other hand, it should be remembered that the object of a rule of this sort is, simply to set an upper limit for general purposes, and not to write specifications for the consulting engineer. If the case requires a closer conformity to a sine wave, it can be so stated in the specifications. Even some other form of test, such as an oscillogram, may be specified, where more information is desired. The important consideration in connection with the Standardization Rules, is to have a simple definition of wave form deviation which can be applied by a simple test, and which will be as nearly as possible a measure of the undesirability of the deviation.

In the case of multi-circuit windings, it is important that the circuits connected in parallel should be of the same phase and wave shape; but this is not always possible with a single hunting tooth, as Mr. Lamme has pointed out. It is possible in many cases, however, with a fractional number of slots per pole per phase.

It is entirely possible so to design an alternator that its no-load wave shape will approach the sinusoidal as closely as it can be measured by any method; and so that it will substantially maintain that wave shape under all conditions of load, single-phase or polyphase, barring the effect of an excessive current distortion produced externally to the alternator, which absorbs an e.m.f., which, subtracted from a sinusoidal generated e.m.f. wave, leaves at the terminals a slight distortion.

Paul M. Lincoln: I want to call the attention of the Committee to a piece of constructive criticism in Mr. Davis's paper. Here is a proposed method of judging wave shape, which I think is a distinct advance on what we had before. It is a method of measuring wave shapes, which takes cognizance of the higher harmonics and penalizes them in the order of those harmonics. That is a feature in the determination of wave shape which we have not had heretofore, and which is a very valuable thing to have.

Some critics have expressed the fear that this allowable latitude given by the proposed factor 1.15 is too large. I am not prepared to express a definite opinion on the exact size of that factor; it may be that further investigation will make it desirable to make some slight modification in its exact value. In this connection we might cite the table appearing in this paper, in which 22 machines are listed. Of these 22 machines three have a form factor above the suggested limit, 1.15. If this list of machines is typical of the ordinary run of machines that come along, I think the rejection of 15 per cent of them indicates we have a fairly close limit.

Another fear has been expressed, nameiy, that the latitude allowed in the lower harmonics is so great as to make a variation in form factor which may give rise to considerable variations in the iron losses of transformers. The one which has been stated

particularly, is the variation in the third harmonic. So far as the third harmonics go, I think we can forget them, because there are practically no third harmonics. In dealing with three-phase circuits we do not get third harmonics in the circuit from one terminal to another. They cannot appear in those circuits, and since practically everything is three-phase, we are reasonably safe in neglecting the effects of third harmonics. Therefore, the fifth harmonic will be the first one which comes in to affect the form factor, and the fifth harmonic, entering to the maximum extent it can under this rule, will not have a very large effect on the iron losses of transformers.

Charles P. Steinmetz: The determination of the wave shape by an oscillogram, the resolution and separation of the higher harmonics, the study of their origin and their elimination, for giving the designer data by which to design machines of good wave shape, is one thing. But to provide a specification to determine by some simple test whether an actual machine will operate satisfactorily in commercial service, and therefore is acceptable, is quite another thing.

The paper deals with the latter consideration. It does not deal with the study of wave shape for the purpose of obtaining the sort of information required by designing engineers. That we have to consider. With regard to the discrimination against higher harmonics, as far as I can remember at the present time, the only condition under which harmonics of the wave are harmful in an electric circuit, is in the case of transmission lines and underground cable systems, that is, in their relation to the capacity of the circuits, and there the harmonic is approximately proportioned to the frequency. Consequently the proposed new standard provides an appropriate criterion. It is not correct to say that the lower harmonics are harmful regarding hysteresis losses. It is not the harmonics there, but the crest value of the voltage wave, which is of significance. That, however, is not determined by the wave shape specification to within 10 per cent for the sine shape alluded to. That may mean a peaked wave or a flat-topped wave, and between the two the difference in core loss is about 36 per cent. So you see that is another question, which is not dealt with in the wave shape specification.

In regard to latitude, the old rules specify that the deviation shall not exceed 10 per cent from the sine shape. It appears to me that to obtain an equivalent with the new specification, we would have to take at random a large number of machines, see how large a percentage of them fall outside the former specification, and ascertain on the new basis the limitations which would result in approximately the same percentage of machines falling outside of the specification. That would give you the equivalent. Then we may consider whether we are ready now to draw the lines closer, make more rigid specifications, and either say (in the terms of the old rule) that the machines must

be within 5 per cent of sine wave, or, (in the terms of the new rule), that the distortion factor must not exceed 1.10. That, however, is entirely aside from the question of the suitable specification for determining the distortion factor.

Charles F. Scott: It seems to me, repeating what others have said, that the means herein given of having a simple practical determination of the variations from sine wave, is an admirable one. However, there may be a case in which machines which may fall within the limitations of the paper may have differences of importance. This test does not indicate whether a single harmonic may cause the limit to be nearly reached, or whether it may be a combination in minor degree of several harmonics. The question then may arise whether the objectionable result of variation from the sine wave may not come from the preeminence of some particular harmonic: For example, one thing in which harmonics may be objectionable is in the induction caused in other circuits. Suppose induction is caused in a telephone circuit. If the harmonic be near the fundamental, say the fifth, it may be too low to cause a disturbance. If it be a high harmonic, several times that frequency, such as the eleventh or thirteenth or higher, then if this permissible limit is nearly reached by the predominance of one high harmonic, a disturbance may result which might not have occurred if the harmonics had distributed throughout the whole range. I bring this point up to illustrate that while the specification is good as far as it goes, there may be cases where it does not cover everything.

L. T. Robinson: Some have urged objections against this method, because it apparently is more complicated than it would be to take the calibrated condenser. I think the proposed method is all right; it makes use of the voltmeter and ammeter, things we are familiar with, and which we know have a certain degree of permanence, as against a condenser which may be permanent to a certain extent, but I do not believe is in the same class as the instruments. Therefore, it is not a complication, but a matter of simplicity.

M. G. Lloyd: I agree with Dr. Steinmetz that it is not a question of whether the departure from the sine wave is harmful or not. In the case of core loss it may be either harmful or beneficial, depending upon the phase of the harmonic. It is a question of how close the wave must be to a true sine wave. If you specify for a transformer a certain core loss, are you satisfied to come within 13.5 per cent or even five per cent of the value you would have with the sine wave?

Taylor Reed: The measurement of wave records is assumed, or authorized by implication, in the Standardization Rules, where a deviation from sine wave of 10 per cent is designated as ordinarily permissible (79, 80, 5e–j). Method and apparatus for determining the deviation, as defined and limited, properly come in for consideration. In measurement of wave records at the present time practise is probably very diverse, and it is

desirable that the measures should be adequate and that those who use them should have a proper understanding of their degree of reliability and accuracy.

The condenser charging current referred to prominently in Mr. Davis' paper is a useful aid in detection and analysis which has received too little attention. Its effect in making prominent the harmonics, as well illustrated in the figures of the paper (Figs. 1 and 3), appears particularly well in case only one harmonic is present in appreciable amplitude. It is also useful as a detector of very small deviations or imperfections in exceedingly good waves where the departure from the sine wave is so small as to be within or near the limit of accuracy of direct wave measurement.

Mr. Davis describes in his paper an interesting combination of condenser and reactance coil by which the reactance of the condenser for generator wave and for sine wave are made directly comparable. The proposed rule based upon its use, tests the generator wave without specific knowledge of the form of the wave: it differs radically from the present rules, notably in penalizing the higher harmonics. The paper does not describe means of transfer to the proposed rule from the present, or correlation between them, as, for instance, comparison under the proposed rule of a generator of new design with a previous generator for which only the wave record might be available, if made by computing the harmonics and magnifying them in proportion to their order, would probably not be reliable or closely made.

The proposed rule, and the apparatus it describes, provides a criterion for waves which is good in many respects. It should be placed under varied and extended test under all possible conditions that have to be met, and its adoption should await general acquaintance on the part of those who would have to apply it, and adequate demonstration of practicability.

The caution Mr. Davis expresses about restricting the wave testing combination to a small part of the rated generator load, which might properly be incorporated in the proposed rule, is very pertinent in view of the excessive sensitiveness of some generators to wave distortion even under small fractional loads. In fact, the load waves at various power factors are of such practical importance that the Standardization Rules seem distinctly incomplete in declaring a generator acceptable on a fair no-load wave, however distorted its load waves may be.

Mr. Davis's apprehension of lack of means of obtaining wave forms would have seemed more justified some years ago when systems were smaller and more isolated, and when oscillographs were less plenty. In fact, while the amount of material obtained by oscillograph now being presented is considerable, it is impossible for one acquainted with the number of oscillographs in operation and with the character of those who have them in charge not to believe that engineering demands requiring its application are

being adequately looked after: and indeed that, further, a large volume of material has been secured, the presentation of which would contribute to the advancement of the art, and to its beauty as well.

Cassius M. Davis: It might be interesting to know the magnitudes of the quantities used in making the twenty-two tests listed in the paper. The condenser had a reactance, on 60 cycles, of approximately 750 ohms. Inserted in series with this was the inductive reactance to give the sine wave, which had about 3000 ohms. The current measured on the ammeter was in the neighborhood of one ampere, and the voltage across the condenser was approximately 700 volts. The question has been raised as to the use of the inductive reactance in series—that we might as well calibrate the condenser in the first place. This reactance is used because the idea of the test is to make it as simple and as rapid as possible, to be purely a commercial test; and if further details are required, an oscillogram should be taken.

Dr. Kennelly suggested the ratio of currents rather than the ratio of reactances of the condenser. This would be possible if the voltage were held constant, but it is frequently difficult to do that, especially if we are using the reactance in series, therefore we would have to read the voltage and current anyhow, which gives the reactance at once.

Mr. Reed brought up the question of correlation between a test which has been made on an old machine under the old rules and a test which may be made on a new machine under the proposed rules. I have calculated a large number of oscillograms, and by taking the ordinates close enough together, or, as has been suggested, by using an analyzer, the oscillogram can be analyzed with sufficient accuracy, to derive the distortion ratio from it; then the wave shapes of the two machines can be compared.

Comfort A. Adams: While such criticisms as we have heard have their place, it should be remembered that the method proposed is a distinct advance over the old one, both in the significance of the definition of distortion and in the simplicity of the method of measuring it; also that the critics have not yet suggested a better one. Unless we find something still better, this should certainly find place in the Standardization Rules.

F. D. Newbury: I wish to recommend the method of calculation of regulation, advocated by Mr. Field, because it is based as nearly as any method can be on test data. The present rule is not adapted to modern machines or modern conditions. Any method that separates the reactance voltage from the armature demagnetization is a step in the right direction. I believe it is still better if separation by calculation is made unnecessary by the test data, as it is in the method recommended by Mr. Field.

S. S. Seyfert: In Mr. Mortensen's paper, the use of the Kapp or the Potier diagram is recommended for the predetermination

of alternator regulation. During 1908 and 1909, Mr. F. T. Leilich and the writer made a study of this subject. The effects of armature reaction and armature impedance were specially investigated. After passing from one to another of a large number of methods of predetermination, a comparatively simple one was arrived at, which gave results checking very closely with those obtained from the direct tests.

The chief faults of the old methods are that they either assume that armature demagnetization may be reduced to an equivalent reactance or that the field current on short circuit is a measure of the true armature reactance. The so-called synchronous reactance obtained from the short circuit test is a fictitious quantity. The reading of the voltmeter across the armature after the short circuit is broken is far in excess of the induced voltage while the current is flowing. When normally loaded, the current of the machine encounters no reactance as large as this. The major portion of the field excitation is directly annulled by the armature demagnetization which is at its maximum value in this case. It seems better, therefore, to compute all voltage drops by using values from the static impedance tests, which are easily made.

In using static impedance values it is necessary, if accuracy is required, to consider the saturation of the machine, and to remember that, for power factors near unity, the minimum value is more correct, while, for power factors near zero, the maximum should be used. The following figures show the comparative values of the *synchronous* and true reactances of the machine on which tests were made.

Apparent synchronous reactance
(I_a=30 amp. I_f=1.2 amp.) 6.30 ohms
Real or static reactance (maximum).....2.84 ohms
Real or static reactance (minimum).....1.92 ohms

In the discussion, Mr. Leilich has outlined the tests required and the essentials of the method. It should be noted that, for any condition of running, the induced armature voltage is found from the terminal voltage by what is virtually the old e.m.f. method, excepting that the *static reactance* is used for getting the armature drop. The armature demagnetization is found and reduced to an equivalent field current by what seems to be a rational method.

The accuracy of the method has been checked for all degrees of saturation of the machine and for power factors other than unity. There was no marked failure of the method for abnormal running conditions.

Comfort A. Adams: It should be noted that regulation tests as made with ordinary instruments and by ordinary observers, are more liable to error than a really careful calculation. I have devoted a great deal of time to this subject, have made very careful measurements, and many calculations by all of these methods, and I have rather come to feel that I would trust

my calculations as closely as observations made by ordinary commercial methods and instruments.

Alexander Gray: My experience has been that the method suggested by Mr. Field is by far the best method. I also think we should carry out his suggestions and guarantee regulation on zero power factor, then we have something which we can test. If we desire a simple method by which to check regulation, then let us use the pessimistic method proposed by Mr. Behrend, and forget about the optimistic method altogether. The majority of alternators have a full-load saturation curve on zero power factor very close to the pessimistic curve. I have seen a few machines of which the full-load zero power factor saturation curve was below the pessimistic curve, due to the enormous increase of field leakage which we have under these conditions.

Comfort A. Adams: The curve calculations I referred to took account of increased field leakage.

Frank T. Leilich: Messrs. Mortensen and Field in their papers on alternator regulation have called attention to a part of the standardization rules that has long needed revision. The late Professor Henry Rowland once remarked, when told that practise did not agree with theory, "So much the worse for the practise." This is the case with the present Standardization Rules regarding the predetermination of regulation; the practise is wrong from a theoretical standpoint and as a consequence the practise gives very poor results.

Mr. Mortensen calls attention to the fact that regulation has been ably handled in a number of papers presented before the Institute and methods proposed for its predetermination which give results in good accord with actual test. Professor Arnold in his celebrated works on design has also given the subject excellent treatment.

The methods which give the best results have in general been open to the criticism that they are rather long and laborious. To get a clear understanding of the principles underlying a rational method of calculating regulation it may be well to outline the factors which cause the voltage of an alternator to fall, when a load is put on the machine. These are:

A. Armature resistance.
B. Armature reactance.
C. Armature demagnetizing action.
D. Increased leakage.

The effect of resistance in causing voltage drop is usually quite small, and, as pointed out by Mr. Field, can in most cases be neglected.

Armature reactance, on the contrary, has a pronounced effect on the voltage regulation and must be considered. Messrs. Hobart and Punga in their paper before the Institute (TRANS. Vol. 23—1904, p. 291) give a method of estimating reactance. Professor Arnold also derives formulas for this factor. In fact, reactance may be calculated from the design data of the machine with a

very fair degree of accuracy. When the machine is on the test floor, why not determine the reactance by direct measurement? This can readily be done by the application of a voltage of the same frequency as the machine is designed for, and measuring the voltage drop across the armature. As is well known, the reactance will vary with the position of the armature bands with respect to the poles and also with the saturation of the iron in the neighborhood of these bands. However, full-load conditions are the ones usually considered and these may be reproduced with sufficient accuracy for reactance measurements by fully exciting the field and having the current in the armature at full-load value.

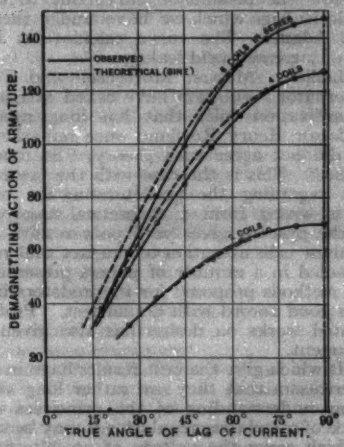


FIG. 8—ARMATURE DEMAGNETIZING ACTION

Under this condition the machine corresponds to a synchronous motor that has fallen out of step and come to a standstill, the armature current being hunted, however, to normal value. Under the above conditions the armature may be jacked around through 180 electrical degrees and the maximum and minimum voltage drops observed. According to experiments, the average reactance may be figured with sufficient accuracy for practical purposes by using the average of the maximum and minimum drops for calculating the impedance, and, from the known value of armature resistance, figuring the reactance.

The sine formula as given by Mr. Mortensen for calculating the armature demagnetizing action will give remarkably close results.

This bucking action of the armature is the principal factor acting to cause a fall in voltage of a generator and it is essential that it be determined as accurately as possible. The curves in Fig. 8 are the results of some experiments performed by Professor Seyfert and the writer, at Lehigh University, to see how close the demagnetizing action as calculated by the formula agrees with actual results. The machine tested was a salient pole revolving field generator so arranged that the number of the coils per phase could be changed at will. The full-line curves are the test results and the dotted curves are sine curves. The curves show that the width of the band of conductors has a slight influence on the demagnetizing action, but on the whole the agreement with the sine law is very close.

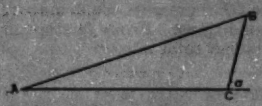


FIG. 9

A B—Ampere-turns for full-load current at O power factor.
C B—Ampere-turns for full-load impedance drop.
A C—Armature demagnetizing ampere-turns at 0 power factor.
a—An angle of which the cosine is equal to the ratio of the armature resistance to impedance.

Mr. Field has given a method of correcting for the increased leakage under load, so that now all quantities affecting regulation may be considered mathematically.

Demagnetizing action as determined from short-circuit conditions is not a true measure of its effect under normal conditions of operation. Referring to Fig. 10, it is clear that a reduction in field strength on the straight part of the saturation curve produces a greater fall in voltage than the same reduction beyond the knee of the curve. However, an assumption that the effects are the same will tend to compensate for the effects of increased leakage, which may then be neglected for most practical calculations.

In conclusion, the following modification of the methods proposed for determining regulation is suggested. With the machine on the test floor, make the following tests:

1. Armature resistance.
2. Armature impedance, from which reactance may easily be calculated.
3. No-load saturation curve.
4. Field ampere-turns for full-load current at zero power factor.

Having the above, the armature demagnetizing ampere-turns for full-load current at zero power factor may be calculated graphically as shown in Fig. 9. Lay off, Fig. 10, the line E_t equal in length to the terminal voltage of the machine at an angle with OX such that the cosine of this angle is equal to the power factor. Draw AB the RI drop, if this is to be considered, parallel to OX. From B draw BC perpendicular to OX and of a length representing the reactance drop. Then OC is the internal voltage of the machine and θ' the total angle of lag.

From the figure it is evident that OD represents the ampere-turns that would be required if demagnetizing action were not present. Step off OE on OC, equal to the demagnetizing ampere-turns of the armature at full-load current, zero power factor, to the same scale as the field ampere-turns. Then OF represents the armature demagnetization under the given conditions. From D step off DG equal to OF, then OG represents the total ampere-turns re-

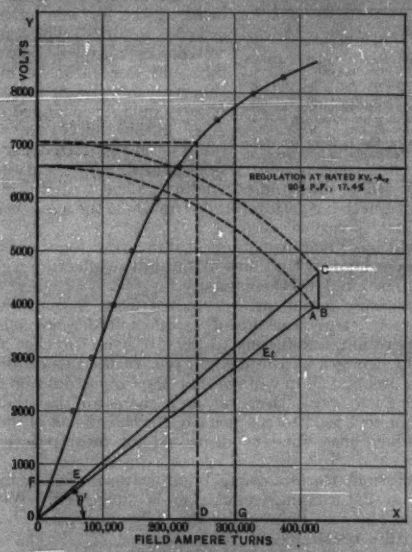


FIG. 10—3600-KV-A. GENERATOR, 6600 VOLTS, THREE-PHASE, 60 CYCLES, 225 REV. PER MIN.

quired for normal load under the given conditions. The intersection with the no-load saturation curve of a vertical line drawn through G gives the value to which the voltage will rise if the load is removed.

This method has been found to give results close to actual test. Inasmuch as all of the quantities admit of predetermination, the calculations may be made from design as well as test data.

W. L. Waters: The Potier triangle method of determining regulation, which is described by Mr. Mortensen, and especially

the empirical method of applying it outlined by Mr. Field, is undoubtedly the most satisfactory method used by designers to-day. But I think it will be well to refer all measurements to a complete zero power factor load saturation curve determined by direct test, rather than to rely too much upon theoretical or empirical deductions. Mr. Field's triangle method requires one zero power factor load reading, and it will require very little more time and expense, and be much more satisfactory, to complete the zero power factor load curve. With this and Mr. Field's recommendation No. 4, we have a reliable basis for checking any regulation guarantee for any power factor from 100 per cent to 0 per cent, and for any current load not greater than the highest value for which the zero power factor curve was determined.

George Smith: The writer can testify to the accuracy as applied to widely different types of alternators of the method proposed in Mr. Mortensen's paper for the calculation of alternator regulation. He would call attention, however, to a method set forth by Professor C. A. Adams in the *Harvard Engineering Journal* in 1902, which is based on the same fundamental principles and is quite as accurate as the method under discussion. Prof. Adams' method appeals to the writer as eliminating all graphical construction. With the armature reaction known, and with the no-load saturation curve, the short-circuit characteristic and armature resistance taken from test, the regulation for any load at any power factor may be calculated by a few simple formulas.

The armature reactance (x) is determined from the short-circuit test. The field m.m.f. at short circuit is used to overcome the armature reaction and the impedance drop. As the resistance is generally small compared with the reactance, the reactance and the impedance may be assumed to be of the same value. Then the reactance drop, IX, may be read directly from the no-load saturation curve at the field strength.

$$F_x = F_s - A$$

where F_s = field ampere-turns giving the current I at short circuit,

and A = the armature reaction at the current I.

With the reactance, X, thus determined, and the resistance, R, taken from test, the virtual generated voltage, E_v, for any load or power factor, may be calculated from

$$E_v = \sqrt{(E\cos\theta + IR)^2 + (E\sin\theta + IX)^2}$$

where E = normal rated voltage
and $\cos\theta$ = power factor of load.

The field strength, F_v, corresponding to E_v is read from the no-load saturation. Then the total field strength, F, required to give the voltage E at the load I is figured from the formula

$$F = \sqrt{\left(F_v + A\,\frac{E\sin\theta + IX}{E_v}\right)^2 + \left(A\,\frac{E\cos\theta + IR}{E_v}\right)^2}$$

The no-load voltage, E_0, corresponding to the field strength F, is then read from the saturation curve and the regulation determined therefrom.

In the application of the above formulas it is to be remembered that the values of voltage, current, resistance and reactance are per phase of the armature windings.

C. J. Fechheimer (by letter): The methods which the authors propose for the determination of the zero power factor curve, from which the curves at other power factors may be determined with sufficient accuracy for any commercial purposes by means of Kapp's diagram, are in general those which are the results of experience and have been found to agree very closely with experimental results.

We wish only to suggest a method for enabling the purchaser or his representative to determine what the inherent regulation of his machine is, without resorting to the test and calculated no-load saturation curve with full-load leakage advocated by Mr. Field, nor to the indeterminate proportions of the triangle of Mr. Mortensen.

We have found from considerable experimentation that the reactance component of the triangle used by both authors can be determined by direct measurement with the rotor removed, the current being circulated at normal frequency in one phase. The voltage then measured will be very close to the reactance drop in the machine with the same current. In order to allow for the armature reaction we can determine this from the short-circuit curve, after allowing for the reactance drop, and determining how many ampere-turns remain. These ampere-turns, however, should be increased in the case of a machine in which the magnetic circuit contains iron which is to some extent saturated, by increasing these ampere-turns by an amount equal to the leakage factor.

In general this factor is 1.1 to 1.3, and sufficiently accurate results could in general be obtained by assuming it to be 1.2 for the Institute rule. This in general gives results which are but very little different from those obtained by actual test at zero power factor.

A. E. Kennelly: I will call on Mr. Lamme to make a summation of the conclusions arrived at thus far in this conference, in his opinion.

B. G. Lamme: It is difficult to state what conclusions can be reached, as a result of the discussions, because we have not

gotten all the evidence together. However, I can make a few definite statements.

When we first took up this question of the revision of the rules, the two sub-committees got together and decided upon certain lines upon which to work, and then later the Sub-committee on Revision took up many of the points which have been discussed in the papers presented at this meeting. One thing, evident all the way through, was that a great many desired rules could not be defined accurately. We could not measure temperature accurately. We could not specify how to make equivalent load tests, and we even could not say how to measure the losses accurately. Apparently, nothing could be done accurately, and yet there has been a general impression that what we have been doing in the past was all right.

So many changes were suggested that it was decided that rather than go ahead and make changes ourselves, we would put the whole matter before the public, present the evidence, and acknowledge that we could not do anything accurately and then find what others thought. It was suggested time and again that we would bring a tempest about our ears, and we have done so to some extent, but we decided that it was better to bring out the facts, and then, if we could not draw any conclusions from an open discussion, we would go ahead as best we could.

From the discussion it appears to be accepted that we cannot obtain accurate results, but in some cases, it seems to me, an exaggerated impression of the inaccuracies has been obtained. Take, for instance, the question of load losses. From the discussion, one might assume that these are very large in many cases. I think one of the reasons why it was thought that the load loss in alternators is excessive is because, in many cases, it was referred to as a percentage of the armature copper losses on short circuit, and this percentage looked rather large. But it must be remembered that the armature copper loss is sometimes relatively small, so that an extra loss of 100 per cent on short circuit may be a very small item in the total losses. It may sound large as a percentage, but the total amount may not be very noticeable.

Take a large turbo-generator, for instance; the copper losses in the armature may be only 20 per cent as great as the iron loss and may be also only 20 per cent as great in the friction and windage, or in effect the copper loss may be only 10 per cent of the other losses, or less than 10 per cent of the total losses. In such cases, it makes but little difference if the armature copper loss is increased 50 per cent, or 100 per cent, since it represents but a small part of the total. Upon analysis, it will be seen that, in general, most of the extra or stray losses are quite small in proportion to the total losses in the machines.

It is the same way with many other things. We must not get an exaggerated idea of the value of the inaccuracies or discrepancies. In most cases, it is possible to get a fair indication

of them. That is what we have been trying to do, in bringing them out in this convention. The fact that we cannot make accurate measurements in many cases, is, from one point of view, rather discouraging. On the other hand, we might say that it is very encouraging to have these facts so fully recognized, for if we cannot make accurate determinations, it is better for everybody to know it, which has not been the case heretofore. It is better to know that we cannot make accurate determinations than to think we can and be wrong about it.

We must consider that while the facts brought out show how indefinite is our understanding of some of the laws with which we are working, yet our admission of ignorance does not really make the application of these laws any more inaccurate than heretofore, and does not make our errors any larger than they were, and it was thought by the Standards Committee that, in bringing these facts forward, we would be conferring a benefit on the industry by showing just what the true situation is.

Heretofore, there has been a general air of confidence concerning many of these things. Until comparatively recently, many of the now questionable points were considered as entirely satisfactory. Electrical designs are now better than ever before, but we now recognize many of the real difficulties, and do not hesitate to tell about them.

Leo Schuler: I wish to congratulate the American Institute of Electrical Engineers and especially the Standards Committee, on this very successful convention, and I must confess that I have learned a great deal, not only from the papers and discussions presented, but also from the general manner in which this Convention was organized and its transactions carried on. I was quite surprised to see how many of your engineers took an active interest in the Standardization Rules, and I shall bring this as a brilliant example before the eyes of my German colleagues.

I wish to thank you, gentlemen, for having not only allowed me to attend your convention, but to take active part in the discussion. I feel sure that the report I am going to make to the German Standards Committee will help us a good deal in the successful completion of our work, and I also hope that the remarks I have occasionally made here will somewhat contribute to make the American and the German Standardization Rules, if not equal, at least comparable.

If you will consider that the world's market of electrical machinery is practically controlled by the American and the German firms, you will understand the importance of such an agreement in the Standardization Rules. I thank you, gentlemen, for the very kind reception you have given me.

A paper presented at the San Francisco Section of the American Institute of Electrical Engineers, February 28, 1913, and at the Los Angeles Section, April 22, 1913.

Copyright 1913. By A. I. E. E.

OPERATION OF TRANSMISSION LINES

BY LEE HAGOOD

This paper will deal with controlling voltage and power factor in transmission lines by means of synchronous machines. The first part will relate to moderate voltage systems having small charging currents but large inductive loads, and the second part to systems having high-voltage transmission lines in which the charging current is considerable. The underlying principles are substantially the same in both cases.

SYSTEMS OPERATING AT MODERATE VOLTAGES

Where the transmission line is short and the voltage is 60,000 volts or below, the charging current is so small that it may be neglected so far as voltage or power factor is concerned.

Fig. 1 represents a transmission line and Fig. 2 a vector diagram illustrating the relation between generator voltage and receiver voltage for an inductive load.

It is assumed that the current, voltage and power factor are measured* at the load end of the line. The actual current, I, lags behind the receiver voltage by the angle θ whose cosine is the power factor; it causes a drop through the resistance, R, in phase with it, *i.e.*, IR can be drawn parallel to I; and causes a drop through the reactance 90 deg. out of phase with I, the current lagging with respect to IX, *i.e.*, IX may be drawn at right angles to I in the direction indicated. The vector E_0 represents the required voltage at the generator end of the line.

*In complex quantities $E_2 = E_1 + I_0 Z$ since $Y = 0$, (see Dr. Steinmetz's formulas, page 868 of this paper) where $I_0 = i_1 + ji_2$ and $Z = r - jx$. Hence $E_2 - E_1 = i_1 r + i_2 x + j\,(i_2 r - i_1 x)$. The imaginary quantity affects the result so slightly that it may be neglected, especially when the power factor is lagging.

By an inspection of Fig. 2, the following is evident:

$$V = E_G - E_R = AD = AB + BC + CD$$

$$AB = IR \cos \theta = I_e R$$

$$BC = IX \sin \theta = I_w X$$

$$CD = E_G - E_G \cos x = E_G (1 - \cos \alpha)$$

Then $V = I_e R + I_w X$ (approximately)

FIG. 1

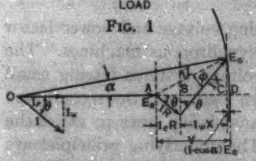


FIG. 2—VECTOR DIAGRAM OF A TRANSMISSION LINE SHOWING RELATION BETWEEN GENERATOR AND RECEIVER VOLTAGE.

E_G = Generator voltage.
E_R = Receiver volts.
V = Voltage drop.
I = Receiver current.
I_e = Energy component of I.
I_w = Wattless component of I.
R = Resistance between E_G and E_R.
X = Reactance between E_G and E_R.
θ = Angle whose cosine is the power factor.
ϕ = Angle whose tangent is R/X.
α = Angle between E_G and E_R.

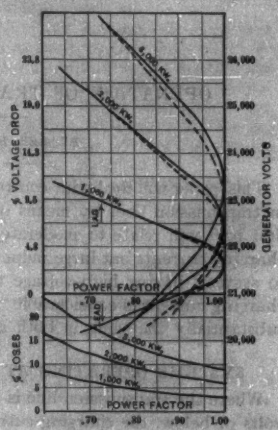


FIG. 3—RELATION OF GENERATOR VOLTAGE TO RECEIVER VOLTAGE FOR DIFFERENT LOADS AND POWER FACTORS FOR A CONSTANT RECEIVING VOLTAGE OF 21,000 VOLTS.

The dotted curves are calculated, using the approximate formula.* For the constants of the line and transformers refer to Table I and Fig. 7.

* The error in using the approximate formula decreases with lagging power factors, with a decrease in ratio of X to R and with a decrease in kilowatts. For a transmission line itself under normal conditions this formula is quite accurate. See Table I, page 867.

The quantity $E_G (1 - \cos \alpha)$ is so small that it may be neglected. In dropping this quantity the maximum error is about two per cent for the usual conditions that arise in practise, which precision is below the requirements of the present problem. This gives us a very simple and convenient formula for voltage drop, viz. $V = I_e R \pm I_w X$; the plus sign should be used if the

current is lagging with respect to the receiver volts, and the negative sign if leading.

Fig. 3 illustrates the effect of power factor on voltage drop in transmitting power. It is assumed that the generator voltage is varied in such a manner as to maintain constant voltage at the receiving end of the line. For simplifying the problem equivalent high-tension voltages and resistance are used. These curves represent a condition where the ratio of resistance to reactance is 0.42, this ratio being tangent ϕ. (See Fig. 2.) Had this ratio been greater, the curves would have been steeper. The dotted curve shows the calculations using the approximate formula, while the full line is accurately calculated.

It is thus seen that when the reactance in a transmission circuit is of any magnitude, the effect of the wattless current on

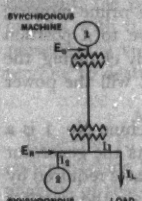


Fig. 4

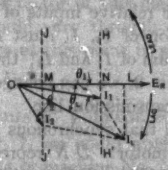


Fig. 5—Current and Power Factor Relation of Two Alternators in Parallel.

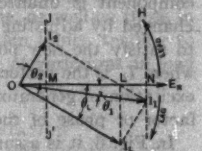


Fig. 6—Current and Power Factor Relations for an Alternator in Parallel with a Synchronous Motor

voltage drop is considerable. With a synchronous machine on the receiver end of the line, we can control this wattless current and therefore regulate the voltage difference. For this method of control, considerable reactance in the circuits involved is a desirable quality.

Phase or Power Factor Control

Fig. 4 is a one-line diagram of a simple transmission system and Fig. 5 is a vector diagram of the phase relations, assuming both machines No. 1 and No. 2 to be synchronous generators, while Fig. 6 illustrates the phase relations assuming machine No. 1 to be a generator and machine No. 2 to be a motor.

Referring to Fig. 5, OL to scale is the kilowatts supplied the load and is equal to ON plus OM, which are the outputs of generators No. 1 and No. 2 respectively. The division of load

between these generators, as with all synchronous generators in parallel, is entirely a question of prime movers; proper division of load may be obtained automatically by means of governors, or non-automatically by hand control of the throttle or water gate, depending upon whether the prime mover in question is a steam engine or waterwheel. In a similar manner the wattless current, or wattless kv-a. of the load, is the algebraic sum of that supplied by the generators, and its division between them is entirely a matter of relative field excitation; suitable division of the load's wattless kv-a. may be obtained automatically by means of voltage regulators, or non-automatically, by hand control of their field rheostats. If the excitation of generator No. 2 is increased, I_2 will increase, but the terminal of this vector necessarily* moves in the locus JJ' because the energy component is unaffected, since division of load can only be changed by adjusting the relative inputs of the prime movers; to satisfy the new position of I_2, I_1 must move to a position where I_L is the vectoral sum of I_1 and I_2; thus by changing the excitation of generator No. 2, we can change at will the power factor or phase of the transmission line.

In Fig. 6, it is assumed that synchronous machine No. 1 is a generator and No. 2 a motor. ON represents the generator output and this equals OM plus OL, the kilowatts required by the motor and load respectively. In this case again the wattless current, or wattless kv-a. of the load is equal to the algebraic sum of the wattless kv-a's. supplied by the synchronous machines. By varying the excitation of the motor, the power factor or phase of the transmission line may be varied at will.

Whether machine No. 2 is a motor or generator, raising its excitation raises the voltage of its busbars, and vice versa. When, for example, we raise the excitation of machine No. 2, we raise the flux and therefore the internal generated e.m.f. and this produces a change in the idle wattless current between the machines, the reaction of which in the armature of No. 1 is equivalent to an increase in field excitation on No. 1. The reaction caused by any tendency towards a new voltage condition on a system, therefore, is a mutual one; the machine

*This statement neglects the fact that any changes in voltage will tend to change the load on the system, since the power consumption of lamps, etc., depends upon the square of the applied voltage. Any change in load on a system simply tends to change the frequency, which in turn actuates the governors on the prime movers, dividing the load according to their individual speed characteristics.

whose excitation is raised suffers a change in its power factor so that an armature reaction occurs, tending to demagnetize its fields, while the other synchronous machines react by changing their power factors, tending to magnetize their fields; the system will thus acquire a new voltage, exciting current being furnished by the machine on which we attempted to raise the voltage to the other synchronous machines in the system. This mutual reaction between synchronous machines occurs whenever the voltage balance between them is disturbed. The magnitude of these phenomena depends mainly upon the number and sizes of the synchronous machines on the system, and the resistance and reactance in the circuits involved.

If we should take any single machine and control its excitation automatically with a voltage regulator, holding the voltage constant, the power factor of this machine, as well as those in parallel with it, would vary through certain limits, tending to preserve the voltage at this point in spite of variations in load tending to destroy it.

Automatic Voltage Regulation

Referring to Fig. 7, we could apply a voltage regulator to either machine No. 1 or machine No. 2 or to both. To make the analysis of this problem simple, it will be assumed that voltage regulators are applied to both machines, and that machine No. 2 is a synchronous condenser. A synchronous condenser is a specially designed synchronous motor for operating without energy load from minimum current to full kv-a. As the maximum losses are quite small, in the magnitude of four per cent of the kv-a. rating of the synchronous condenser, their consideration for the present will be neglected.

Since the voltage drop is constant, the wattless current, I_w, which must be maintained in the transmission line at the receiver end for different loads, can be obtained from the following equation:

$$I_w = \frac{V - I_e R}{X}$$

and the energy component of the current (for a three-phase circuit) is

$$I_e = \frac{\text{kilowatts}}{E_R \times 1.73}$$

The actual current at the receiving end of the line is therefore

$$I = \sqrt{I_e^2 + I_w^2}$$

and the actual power factor at the receiving end of the line is

$$\cos \theta = I_e/I$$

All of these quantities have been plotted in Fig. 8 for a given condition of voltage drop and resistance and reactance.

To obtain the synchronous condenser current, which is substantially wattless, we first determine the wattless current of the load, viz:

$$I_{WL} = I_e \tan \theta_L$$

and the synchronous condenser current will be

$$I_s = I_{WL} \mp I_W$$

The minus sign should be used if I_W is lagging and the plus sign if it is leading. Fig. 9 gives two sets of synchronous condenser curves, one assuming the load to have a constant power factor of 0.8 and the other of 0.6.

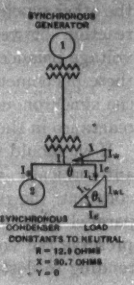


FIG. 7

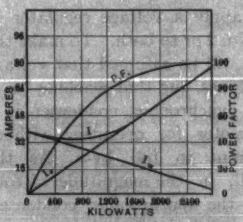


FIG. 8—ILLUSTRATES RELATION OF CURRENT, ITS ENERGY AND WATTLESS COMPONENT, TO THE KILOWATTS FOR CONSTANT VOLTAGE DROP

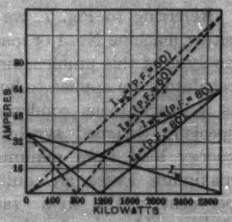
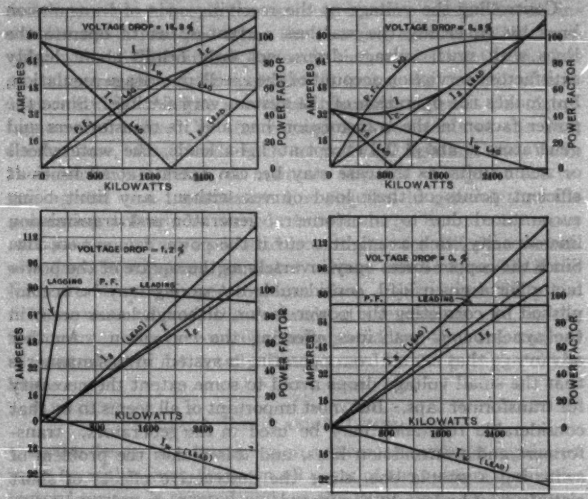


FIG. 9—ILLUSTRATES THE WATTLESS CURRENT FROM A SYNCHRONOUS MACHINE TO MAINTAIN CONSTANT VOLTAGE DROP. TWO CONDITIONS OF LOAD ARE ASSUMED; ONE AT 0.6 AND THE OTHER AT 0.8 POWER FACTOR.

Figs. 10, 11, 12 and 13 illustrate the effect of maintaining different voltage differences between the generating and receiving ends of a certain transmission line. The values of voltage drops are taken at 18.8, 8.8, 1.2 and 0 per cent. It may be noted that the power factor appears to approach some constant value for all loads as the voltage difference becomes small. This

condition occurs when the line I_r intersects I_w at the origin, which is the condition of zero voltage difference, if the capacity current is negligible. The value of the power factor under this condition approaches unity as the ratio of R to X increases, this ratio being the tangent of angle ϕ. These data apply to the transmission line illustrated in Fig. 7. It is a three-phase, 22 000-



FIGS. 10, 11, 12 AND 13—SHOW THE RELATIONS FOR VOLTAGE DROPS* OF 18.8, 8.8, 1.2 AND 0 PER CENT, RESPECTIVELY, FOR THE SYSTEM IN FIG. 7.

The equivalent high-tension resistance and reactance to neutral are 12.9 and 30.7 ohms, respectively. The equivalent high-tension receiving voltage is 21,000 volts. The synchronous condenser current is based on a load of 0.7 power factor.

*Calculated by the approximate method, the accuracy of which is within the limits of practical requirements. For accurate calculations the method illustrated in Figs. 18, 19 and 20 may be used.

volt, 60-cycle line, 12.7 miles (20.37 km.) long, consisting of three No. 2 copper conductors spaced 30 in. (76.2 cm.). The resistance and reactance given are phase to phase values, and include the transformers.

Evidently, if the voltage established at the receiving and generating end of a transmission line is such that the voltage drop is

small, the voltage at the receiver end being controlled by a synchronous machine with a voltage regulator, there is no necessity for a voltage regulator at the generating station. It becomes practical, therefore, to operate a system* by controlling the voltage at the distribution centers by means of synchronous condensers with voltage regulators, without using voltage regulators on any of the generators.

Controlling the voltage at the receiving ends of transmission lines by governing the wattless current so as to operate the lines with small voltage drops, not only brings about highly satisfactory service on account of the excellent voltage regulation, but makes the operation of the system very flexible. Since the power factor in the transmission line and its transformers and generators is above 0.9 except at light loads, the waterwheels or steam units, as the case may be, can operate at all times at efficient points of their load curves without any limit being encountered due to transformers, generator and transmission line capacity, such as might occur if the power factor were low. Since the copper losses vary inversely as the square of the power factor for a given load, considerable net saving may be accomplished by correcting the power factor, although losses occur in the synchronous machines effecting the correction. Another advantage that comes from operating a system in this manner is that the small voltage drops avoid to some extent the necessity for transformer taps. But most important of all seems to be that considerable reactance may be used in the generators, transformers and transmission lines, and this makes the problem of switching a simple one, since the destructive effects of short circuits may be largely eliminated.

HIGH-VOLTAGE TRANSMISSION SYSTEMS

In the transmission of power over a long high-voltage line, say for voltages of 60,000 volts and higher, the exciting or wattless currents which must be provided are not only those for the induction motors, transformers, etc., but whatever is required by the transmission line itself. A transmission line has both inductance and capacity, both of which require exciting current. The leading current required by the capacity is of very much greater magnitude than the lagging current required by the in-

*For a description of a system so operated see the author's article in the *General Electric Review* for December, 1912, entitled "Operation of Synchronous Machines in Parallel."

ductance, hence the exciting current to charge a transmission line is always leading, that is, with reference to the generators. To charge a line by means of a synchronous motor requires lagging current. On some of the 110,000-volt lines, as much as 10,000 kv-a. is required to charge a single line under normal voltage conditions. Even considerably more than this is necessary for 140,000-volt lines.

It may appear that a happy solution of the voltage and power factor problem arises if the exciting currents caused by an induction motor load just offset the charging current of the transmission line. The difficulty arises in such a case that the number of induction motors in operation is under the control of customers and is therefore a variable quantity, whereas the charging current is fixed by the voltage and constants of the line; furthermore, other loads such as railway, lighting, etc., have their variations: hence, to maintain suitable voltage at the receiving end of a transmission line requires in general that the generating voltage be varied through large limits. In many stations the characteristic load is such that for different periods of a day the necessary generator voltage can be foretold; if the lines are short the operators can often adjust successfully the field currents to meet the demands at the receiver end, or the field current may be controlled automatically. But this method of control may be totally inadequate for long high-voltage lines.

Voltage Regulation Limitations

In the design of a transmission system, the voltage regulation must be within such limits on all parts of the system that satisfactory service is secured and, at the same time, all the transformers obtain proper exciting voltages and the lightning arresters be exposed only to safe dynamic voltages.

Service for lighting loads is very exacting, since a 2 per cent variation in voltage causes a change of approximately 8 per cent in candle power. Service for power loads is not so exacting; nevertheless, it is of considerable importance, because on reduced voltage the starting torque and maximum horse power of induction motors fall off as the square of the voltage. Since the power consumed by any load falls off approximately as the square of the voltage, it is of great importance to power companies that the voltage be maintained as high as is consistent with satisfactory service.

Transformers should have proper exciting voltage, because in general, a departure from normal rated voltage reduces the capacity for a given heating rise. By exciting voltage is meant the voltage applied on the side from whence the power comes. Reducing the voltage by a given per cent reduces the kv-a. capacity substantially by the same per cent, since the ampere capacity depends on the size of conductors. Increasing the voltage above normal decreases the output, because the exciting current is increased and also the core losses. Just how much increased losses occur for a given over-voltage depends upon characteristics in design, but it is safe practise, in general, never to exceed say 5 per cent of the rated voltage.

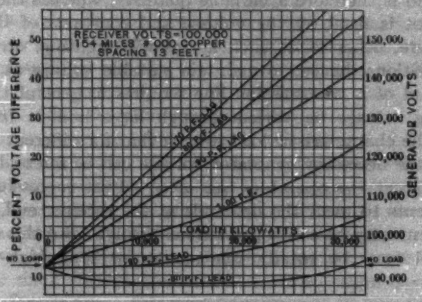


FIG. 14—SHOWS THE GENERATOR VOLTAGES TO MAINTAIN A RECEIVER VOLTAGE OF 100,000 VOLTS FOR DIFFERENT POWER FACTORS AND KILOWATTS. THE TRANSFORMER CONSTANTS ARE INCLUDED.

To prevent lightning arresters from being endangered by over-voltage, they should not be exposed to a voltage regulation exceeding 15 or 20 per cent. Lightning arresters are designed to protect against transient voltages, and their characteristics are such that they offer protection only around the normal voltage rating. Should a lightning arrester be called upon to relieve a transient voltage, when the dynamic or steady voltage of the system was 15 or 20 per cent above that at which the lightning arrester was charged, it would be exposed to serious damage, on account of the large flow of current occurring. Hence, it is not considered safe practise to expose a lightning arrester equipment to a voltage regulation exceeding 15 or 20 per cent.

Effect of Power Factor at Receiver on Voltage Drop

Figs. 14 and 15 illustrate the effect of voltage drop for different loads and power factors, while Fig. 16 shows the system to which the data apply. In Fig. 14 the ordinates represent the kilowatts supplied the receiver and the abscissas the voltages at the generators. Equivalent high-tension values of voltage are used, the per cent difference being between the generator and receiver low-tension busbars, since the transformer reactance has been included in the calculation. For example, if 20,000 kw. at 0.8 power factor were required by the receiver at 100,000 volts, the generator voltage would have to be 132,000 volts, or 32 per cent above the receiver volts, and at no-load, to maintain the same receiver volts, the generator volts would have to be 93,000 volts, or 7⅞ per cent below the receiver volts, causing a total range at the generating station of 39 per cent. This is, of course, an operating condition impracticable to meet. Fig. 15 gives a set of curves where the generator voltage is plotted against power factor. For example, suppose 20,000 kw. were to be received at 100,000 volts, the curve for this load shows the different voltages that would be required at the generating station for different power factors at the receiver.

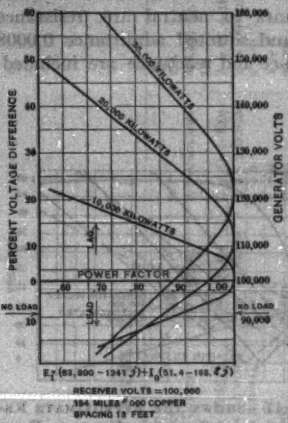


Fig. 15—Illustrates the Generator Voltages for Different Kilowatts to Maintain a Receiver Voltage of 100,000 Volts, Assuming the Power Factor of the Receiver at Different Values.

For a given set of conditions on a long transmission line, the power factor varies at different points along the line, due to the effect of the distributed capacity. The only points which need be considered are the generator and receiver ends of the line, since the power factors here determine the kv-a. capacities of the generators and transformers. As will be seen below, the power factors at these points for a given transmission line depend upon the voltage difference.

Constant Voltage Drop

As with the lines previously considered, having negligible charging current, as soon as the voltage is fixed at two points, fixed conditions of power factor are established from no load to full load, independently of the power factor of the load.

Fig. 16 is a one-line diagram of a system. The transmission line is 154 miles long, the conductors being No. 000 copper, spaced 10 feet in a vertical plane, which is equivalent to 13 ft. (3.96 m.) equilaterally. The constants to neutral are, resistance 53.9 ohms, reactance 171 ohms and shunted admittance 0.0008 mhos. The transformer resistance and reactance are included.

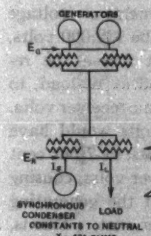


Fig. 16—(The Characteristics of this Line are given in Col. 2, Table I.)

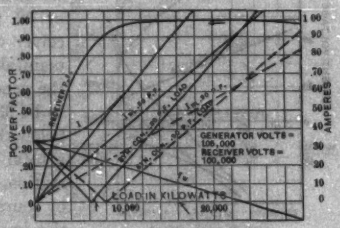


Fig. 17—Shows the Approximate Relations for a Constant Voltage Drop of 5 per cent for the Line in Fig. 16.

It will be assumed that this line is to be operated at five per cent voltage drop, constant voltage being maintained by voltage regulators on the generators and synchronous condenser.

As it will simplify the problem, first the approximate relations will be established and then the same general results obtained accurately.

The following approximate formula applies for voltage drop, as follows:

$$V = I_cR + I_wX - I_cX/2$$

This formula is a modification of that already given to include the charging current I_c. Since the capacity is distributed

TABLE I

Length of line in miles	12.74		153.4		153.4		127		275		275	
Size of conductor	No. 2 Copper		3/0 Copper		3/0 Copper		5/0 Aluminum		605,000 cir. mil.		605,000 cir. mil.	
Equilateral spacing, feet	2.5		13		13		13		14		14	
Line constants to neutral	$Z = 10.5-8.8j$		$Z = 50-127j$		$Z = 50-127j$		$Z = 41.4-100j$		$Z = 41.4-171j$		$Z = 41.4-171j$	
	$Y = 0$		$Y = -0.0008j$		$Y = -0.0008j$		$Y = -0.006930j$		$Y = -0.00132j$		$Y = -0.00132j$	
Transformer constants to neutral	$Z = 2.5-21.8j$		$Z = 3.9-44j$		$Z = 0$		$Z = 0$		$Z = 0$		$Z = 0$	
	$Y = 0$		$Y = 0$		$Y = 0$		$Y = 0$		$Y = 0$		$Y = 0$	
Load in kw.	2,000		20,000		20,000		20,000		20,000		50,000	
Voltage at receiver	21,000		100,000		100,000		100,000		140,000		140,000	
Power factor at receiver	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.85	1.00	0.85
Generator voltage (accurate)	22,400	24,500	109,100	132,000	108,000	124,500	106,800	120,000	132,000	146,000	140,000	182,000
Generator voltage (approximately)	22,200	24,400	103,900	129,500	105,000	123,800	105,200	119,600	130,000	146,500	139,000	176,500
Per cent error	0.8	0.4	4.8	1.9	2.8	0.6	1.5	0.3	1.5	0.3	0.7	3.0

The above table gives the characteristics of the various transmission lines referred to in the text. As a matter of interest a comparison is shown to illustrate the accuracy of the approximate formula on page 866. The error is quite small except in column 2, where the constants of the transformer were included.

along the line, we can assume that the voltage drop is approximately $I_cX/2$. The actual wattless current in the receiver end of the line is I_w. For most conditions this formula will be accurate within a few per cent. Table I gives an idea as to the limitations of its use.

Fig. 17 shows a set of curves similar to those in Figs. 8 and 9. For simplicity it is assumed that the synchronous condenser losses are negligible. The current required by the synchronous condenser will depend upon I_w, the amount of wattless current which must be maintained in the receiver end of the line for a given voltage difference, and upon the load's wattless current I_{wL}. For the sake of comparison two conditions of load are assumed, one at 0.8 power factor and another at 0.9 power factor. The actual current at the receiver end of the line is, of course, independent of the load's power factor, but depends upon the voltage difference maintained and the kilowatts delivered.

Results obtained in the above manner are accurate enough for a preliminary examination of a problem, but for important calculations greater accuracy is necessary. Dr. Steinmetz has made possible a very simple solution of the problem by the following formulas*, viz:

$$E_1 = E_0 (1 + ZY/2) + I_0 Z (1 + ZY/6).$$
$$I_1 = I_0 (1 + ZY/2) + E_0 Y (1 + ZY/6).$$

These equations involve complex quantities; E_1 and I_1, and E_0 and I_0 represent the voltage and current at the generator and receiver ends respectively, while Z and Y are the impedance and shunted admittance between the points in question.

Thus, by knowing the constants of a line and assuming the voltage, kilowatts and power factor at the receiving end, the voltage, kilowatts and power factor of the generating end can be determined as well as the efficiency of transmission. Fortunately it works out here, as with those lines where the charging current is negligible, that for a given voltage difference, the relation of wattless current, or wattless kv-a. in the receiver end of the line has a straight line relation with the kilowatts.

Fig. 20 is a set of curves similar to those in Fig. 17. The

*For a solution of a problem with these formulas see article by F. W. Peek in the June 1913 number of the *General Electric Review*, entitled "Practical Calculations of Long-Distance Transmission Line Characteristics."

voltage difference and line constants are the same. Since the line "Receiver Wattless kv-a." in Fig. 20 has a straight line relation with the kilowatts, only two points are necessary for its location. It is convenient to locate one point by the amount of wattless lagging kv-a. in the receiving end of the line which will give the specified voltage drop at zero load. Fig. 18 is a curve from which the information may be obtained, it being 8500 wattless lagging kv-a. for a voltage drop of 5 per cent. Another convenient point is where the kilowatts transmitted is at unity power factor, that is where the "Receiver Wattless kv-a." is zero, gives the same voltage drop. Fig. 19 is the curve from which this information may be obtained, it being 13,000 kw. at unity power factor for a 5 per cent voltage drop. Thus the line "Receiver Wattless kv-a." can be established and from it the receiver kv-a. and power factor as well as the synchronous condenser kv-a., for different values of kilowatts. To determine the kilowatts and power factor at the generator end involves the use of the complex equations. It will be found that the voltages calculated will check up with the assumption that for a given voltage difference the wattless kv-a. in the receiver end of a line has a straight line relation with the kilowatts.

Fig. 21 gives the values of voltage at which the generators must operate, if no synchronous condensers are used, and a voltage of 100,000 volts is to be maintained for a load of 0.8 power factor. The efficiency of transmission and the generator power factor is also given. It would not be very satisfactory to operate the generators at voltages higher than about 15 per cent above the receiver, since this would involve a total range in voltage at the generator station of about 23 per cent. A maximum load of about 12,000 kw. at 0.8 power factor could be carried with a 15 per cent drop. As may be seen from Fig. 20, 30,000 kw. could be delivered over the same line with better efficiency and better power factor with a constant voltage drop from no-load to full load of 5 per cent.

Operating a system at small voltage drops in transmission would offer the advantage that all the transformers could be standardized for one voltage and the troublesome question of transformer taps could be avoided. The wattless corrective kv-a. to control the power factor of a transmission line and hence its voltage, need not all be under automatic control, but just so much as is necessary to control any tendency towards voltage changes. In the case cited, all the power was taken off the end

of the line, and the wattless corrective kv-a. was applied at that point. As a matter of fact the load could be applied at several points along the line, and synchronous machines used at these points to control the voltage. Some of the synchronous machines could be in the secondary distribution at very remote points from the main transmission line; in fact, the further away the better, since the power factor correction would improve the condition in the circuit in question as well as in the main transmission line. It is thus possible to operate an entire system with

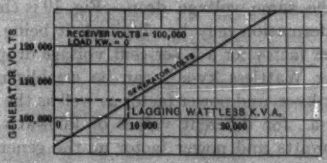


FIG. 18—GENERATOR VOLTS TO MAINTAIN RECEIVER VOLTAGE OF 100,000 FOR ZERO KILOWATTS AND DIFFERENT AMOUNTS OF WATTLESS KV-A. AT THE RECEIVER

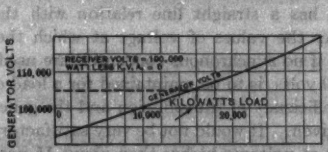


FIG. 19—GENERATOR VOLTS TO MAINTAIN RECEIVER VOLTAGE OF 100,000 FOR ZERO WATTLESS KV-A. AND DIFFERENT AMOUNTS OF KILOWATTS AT THE RECEIVER: THAT IS, THE POWER FACTOR AT THE RECEIVER END IS ASSUMED AT 1.00 FOR ALL LOADS.

voltage drops of little consequence; in fact, the voltage of any system can be controlled entirely by means of synchronous condensers with voltage regulators located at the principal centers of distribution, without using voltage regulators on the generators.

In Fig. 20, the voltage drop was taken at 5 per cent. By making the difference greater, a smaller amount of wattless corrective kv-a. would be required. However, the voltage difference should not exceed a certain amount depending upon the constants of the transmission line, otherwise too much lagging current would be required at light loads.

Generator Voltage Varied with Load to Supply Constant Receiver Voltage

To meet the requirements of high efficiency and favorable use of the available kv-a. of the generator and transformer capacities, the voltage drop can be increased as the load comes on. This may be done in such a manner as to make maximum use

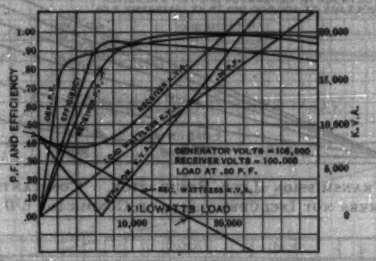


Fig. 20—Shows the Accurate Relations for a Constant Voltage Drop of 5 Per Cent for the Line in Fig. 16

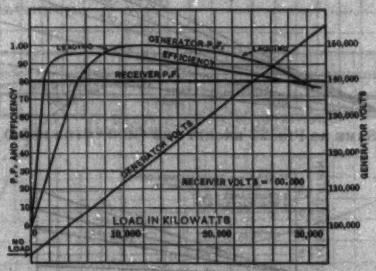


Fig. 21—Shows the Relations if the Voltage Drop is Not Controlled for the Line in Fig. 16

of a given number of synchronous condensers with voltage regulators.

A concrete example of design will be given to illustrate the practical value of this application: Assume a transmission system consisting of two lines 127 miles (204.4 km.) long, each having three steel reinforced aluminum conductors spaced 10 ft.

(3 m.) in a vertical plane, and two synchronous condensers normally rated at 5000 kv-a. located at the receiver end of the line. It will be assumed that 42,000 kw. is the maximum output of the generating station and this is to be applied normally over two

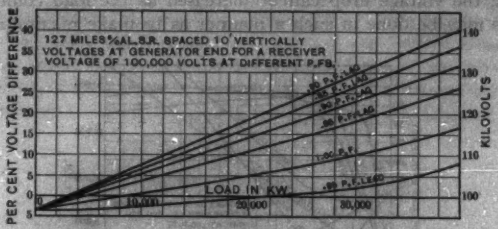


FIG. 22—TRANSMISSION LINE REGULATION. CONSTANTS OF TRANSFORMERS NOT INCLUDED. SIZE OF CONDUCTOR 6/0 ALUMINUM

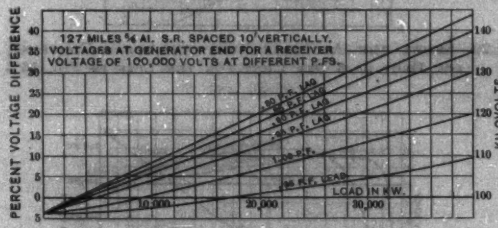


FIG. 23—SAME AS FIG. 22 EXCEPT THE CONDUCTOR IS 5/0 ALUMINUM

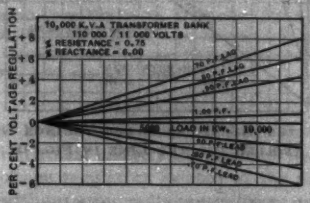


FIG. 24—VOLTAGE REGULATION OF A 10,000-KV-A. TRANSFORMER

lines, but in case of trouble, one line must carry the entire output. Since the nature of the use of the synchronous condensers involves their operation on rather poor load factors, the 25 per cent overload rating will be used in the calculation. The actual

energy consumed by each synchronous condenser will be about 200 kw. at its full kv-a. load. It will be assumed also that four 10,000-kv-a. banks of transformers are located at both the generating and receiving ends of the line.

It will simplify the problem, as well as lead to greater accuracy,

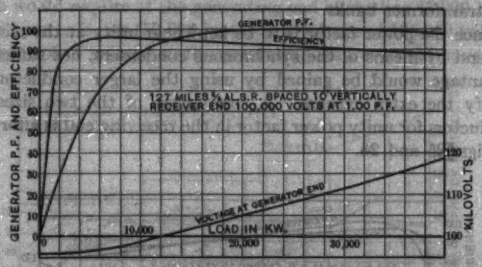


FIG. 25—RELATIONS AT GENERATOR END OF LINE FOR AN ASSUMED RECEIVER VOLTAGE OF 100,000 AND POWER FACTOR OF 1.00. TRANSFORMER CONSTANTS INCLUDED AT GENERATOR END ONLY. SIZE OF CONDUCTOR 6/0 ALUMINUM.

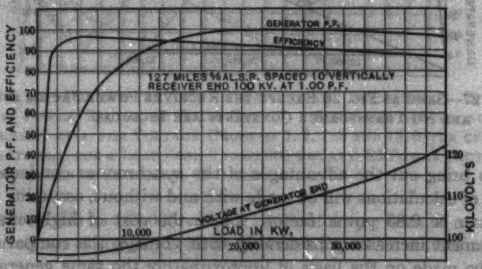


FIG. 26—SAME AS FIG. 25 EXCEPT THE CONDUCTOR IS 5/0 ALUMINUM

if the transmission line is considered separately from the transformers. A slight error would occur if the transformers and line were treated as one, because the capacity of the line is distributed.

What little capacity occurs in the transformer itself may be neglected. Hence the calculations below are given for the line and transformer separately. Since the spacing of conductors

is considerable for the higher voltages, the reactance introduced thereby is great. Increasing the size of conductors therefore will help but slightly in the matter of voltage regulation. Figs. 22 and 23 afford a comparison between 6/0 and 5/0 steel-reinforced aluminum conductors. Fig. 24 is a set of curves to illustrate the regulation at different power factors for any one of the transformer banks.

Since the power factor is to be kept near unity at the receiving end by means of the synchronous condensers, not sufficient advantage would be gained by using the larger conductor to justify the extra expense. A comparison of the two sizes of conductors for unity power factor in the receiving end is afforded in Figs. 25 and 26.

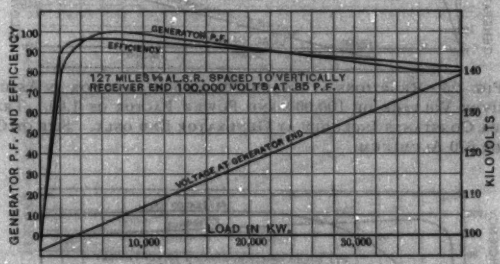


FIG. 27—SAME AS FIG. 26 EXCEPT THE RECEIVER POWER FACTOR IS 0.85 AND NO TRANSFORMER CONSTANTS ARE INCLUDED

To bring out the advantages of the synchronous condensers, a set of calculations will be made with and without, assuming the load to be 0.85 power factor. Since the cost of high-tension equipment increases considerably with voltage, the comparison will be made on the basis of approximately the same generator voltage. To simplify the calculation, the effect of the transformers will be neglected, as this will not injure the accuracy of the comparison to any marked extent.

WITHOUT SYNCHRONOUS CONDENSERS

Refer to Fig. 27 and to Table II. With both lines in parallel a load of 38,600 kw. at 0.85 power factor and 100,000 volts can be carried at an efficiency of 92 per cent, which would re-

quire at the generating end 42,000 kw. at 0.93 power factor (45,000 kv-a.) and a voltage of 117,000 volts; the control of voltage at the generating end of the line would have to be from 96,000 to 117,000 volts, a range of 21 per cent, if a constant voltage of 100,000 volts be maintained at the receiving end of the line.

With only one line, a load of 35,600 kw. at 0.85 power factor and 100,000 volts could be carried at an efficiency of 85 per cent, which would require at the generating end of the line 42,000 kw. at 0.83 power factor (50,600 kv-a.) at a voltage of 135,000 volts. The control of voltage at the generating station would have to

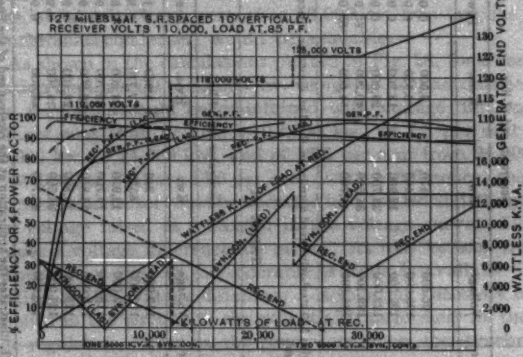


FIG. 28—ILLUSTRATES THE RELATIONS OF TRANSMISSION EFFICIENCY, POWER FACTOR AT EACH END OF A LINE AND SYNCHRONOUS CONDENSER KV-A. FOR VOLTAGE DROPS OF 1. 7, 7.3 AND 13.6 PER CENT, RESPECTIVELY, FOR A LOAD FROM 0 TO 30,000 KW. AT 0.85 POWER FACTOR. NO TRANSFORMER CONSTANTS INCLUDED.

be from 96,000 to 135,000 volts, a range of 41 per cent, if a constant voltage of 100,000 volts at the receiving end is maintained.

WITH SYNCHRONOUS CONDENSERS

Refer to Fig. 28 and Table III. Fig. 28 illustrates the effect of varying the voltage difference in order to increase the voltage range of operation of the synchronous condenser: whenever the voltage drop is changed, the synchronous condenser will automatically take a new point in operation on its phase curve. It is assumed in this case that voltage regulators are used on the machines at both ends of the line.

TABLE II

Receiver end of line			Load	Generator end of line				Transmission line	
Kv-a.	Kw.	Power factor	Power factor	Voltage	Kw.	Kv-a.	Power factor	Efficiency	Volts difference
0	0	0.0	0.0	96,600	170	6,600	0.026 lead	0.0	3.4% rise
7,300	6,200	0.85	0.85	103,000	6,460	6,520	0.99 "	96.0	3.0% drop
14,400	12,200	0.85	0.85	109,500	12,900	13,200	0.978 lag	94.7	9.5% "
29,200	24,000	0.85	0.85	122,000	26,700	29,600	0.90 "	90.0	22.0% "
35,300	30,000	0.85	0.85	129,100	34,500	40,200	85.9 "	87.0	29.1% "
43,700	38,000	0.85	0.85	135,500	44,700	54,600	82.0 "	85.0	35.5% "

This table refers to a transmission line 127 miles long with 5/0 steel-reinforced aluminum, 0.66 in. diameter, spaced 10 ft. vertically, on the assumption that the load on the line is at 100,000 volts and 0.85 power factor.

TABLE III

Receiver end of line			Load	Generator end of line				Transmission line	
Kv-a.	Kw.	Power factor	Power factor	Voltage	Kw.	Kv-a.	Power factor	Efficiency	Volts difference
6,600	200	0.03	0.00	112,000	249	1,960	0.12 lead	80.4%	1.7% drop
7,300	6,200	0.85	0.85	112,000	6350	7,710	0.83 "	98.4%	1.7% "
12,000	12,200	0.999	0.85	112,000	12,920	14,200	0.91 "	94.5%	1.7% "
14,400	12,200	0.85	0.85	118,000	12,700	12,700	0.999 "	95.4%	7.3% "
24,000	24,000	0.997	0.85	118,000	25,850	26,000	0.995 "	93.0%	7.3% "
25,900	24,000	0.927	0.85	125,000	25,800	26,400	0.981 lag	93.1%	13.6% "
30,600	30,000	0.982	0.85	125,000	33,300	33,500	0.994 "	90.2%	13.6% "
39,400	38,000	0.965	0.85	133,000	42,700	44,400	0.962 "	89.0%	21.0% "

This table refers to the same line covered by Table II, illustrates the application at the receiver end of the line of two 5000-kv-a. synchronous condensers controlled by voltage regulators. It is assumed that the load has a constant power factor of 0.85 at 110,000 volts.

With both lines in parallel, a load of 39,400 kw. at 0.85 power factor and 110,000 volts can be carried at an efficiency of 94 per cent, which would require at the generating end 42,000 kw. at unity power factor (42,000 kv-a.) and a voltage of about 118,000. The power factor of the receiver end of the line would be 0.98. The voltage at both ends of the line would be held constant by the voltage regulators, in spite of variations in load. With one line, a load of 37,000 kw. at 0.85 power factor and 110,000 volts can be carried at 89 per cent efficiency, which would require at the generating end of the line 42,000 kw. at 0.98 power factor (42,500 kv-a.) and a voltage of 132,000. The power factor at the receiver end of the line would be 0.96. It is assumed that, in the case of transmitting more than 18,000 kw. over one line, both synchronous condensers would be available.

As shown in the calculations plotted in Fig. 28, for a range of station load from 0 to 42,000 kw. using one line, automatic voltage regulation could be maintained with voltage difference of 1.7 per cent from no-load to 12,000 kw., of 7.3 per cent from 12,000 kw. to 24,000 kw., and of 13.6 per cent from 24,000 kw. to 30,000 kw. Above 13.6 per cent voltage difference, the synchronous condenser could be operated fully loaded and the generator voltage raised as indicated in the voltage curve. Definite values of voltage difference are given. As may be seen from an inspection of Fig. 28, considerable latitude is available in the setting of this voltage difference. Regulating rheostats can be applied in the circuits of the potential transformers for the voltage regulators, either on the generators or on the synchronous condensers, or on both, and by adjusting them the voltage settings of the regulators can be changed without any adjustments in the regulator itself. In actual operation only such settings should be given, whenever practicable, as bring about the voltage difference that causes the best efficiencies and most favorable use of the available kv-a. capacities of the generators and transformers.

Comparing the use of one line to deliver all the power, 42,000 kw., with and without the synchronous condensers, we have the following: voltage regulation at generator end of line 18 per cent against 39 per cent, generator kv-a. 42,500 against 50,600, receiver kv-a. 37,800 against 42,000, and efficiencies 89 per cent against 85 per cent. The voltage regulation without the synchronous condensers is excessive for successful operation; the application of 13,500 kv-a. in synchronous condensers reduces the

kv-a. in the generating station and its transformers by 8000 kv-a. and in the receiver transformers by 4200 kv-a., the price of which offsets the investment for the synchronous condensers; and furthermore, the application of the synchronous condenser, due to the improved efficiency, increases the output of the line 1400 kw.; allowing 400 kw. for losses in the synchronous condensers, a net saving of 1000 kw. is obtained.

Flexible Generator and Receiver Voltages

At a distribution center, it is very desirable to have a flexible voltage, which can be increased as the load comes on, because with power feeders, the voltage drop due to load may thus be compensated for within proper limits, and with lighting feeders, the feeder regulators are enabled to operate within limits of accurate regulation.

A flexible generator and receiver voltage may be accomplished by means of a synchronous condenser and series booster, both machines arranged on the same shaft. The excitation of the synchronous condenser should be controlled with a voltage regulator and that of the booster by hand control. At the generating stations, the excitation should also be controlled by a voltage regulator. At both stations, regulating rheostats should be installed in the circuits of the potential transformers of the voltage regulators. By means of these regulating rheostats, the voltage setting of the busbars can be changed at the will of the operator.

Fig. 29 shows a one-line diagram of a system. In station C are shown a synchronous condenser and booster for each line. The line constants are assumed the same as those used for calculating curves in Fig. 28. Referring to Fig. 28, it will be seen that, for a given voltage difference and an assumed power factor for the load, the kv-a. of the synchronous condenser will vary definitely with the kilowatt load, and by changing the voltage difference, the kv-a. of the synchronous condenser may be changed: thus, controlling the voltage difference, gives a control of the kv-a. load on the synchronous condenser. An equivalent effect to this can be established by holding the voltage constant in both stations and compensating for voltage by means of a synchronous booster.

The function of the synchronous booster, therefore, is to effect voltage compensation, the amount of buck or boost being controlled by the field excitation. When used in connection with

a synchronous condenser, controlled by a voltage regulator, a means of controlling the wattless kv-a. is effected. Without the booster, for a given voltage setting at the generating and receiving stations, the wattless kv-a. supplied by the synchronous condenser will depend upon the kilowatts load for a given assumed power factor. With the booster, whenever the synchronous condenser comes up to its overload limit, the field exci-

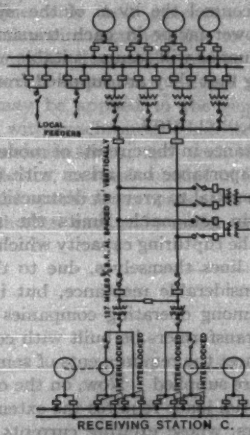


FIG. 29—ONE-LINE DIAGRAM* OF A SYSTEM TO ILLUSTRATE AN APPLICATION OF A SYNCHRONOUS CONDENSER WITH A DIRECT-CONNECTED SYNCHRONOUS BOOSTER. THE SWITCHES MARKED "INTERLOCKED" ARE SIMPLY TO AFFORD PROVISION FOR CUTTING OUT THE BOOSTER.

* All the disconnecting switches necessary are not shown. For example, each oil switch must be so protected by disconnecting switches that it can be made "dead" to allow repair work. Also provision must be made for testing either line without involving but one generator and transformer.

tation of the booster can be changed to reduce its kv-a. load, without affecting the voltage at either the generating or receiving station, and conversely, when the voltage setting at either station is changed, tending to bring the synchronous condenser kv-a. to an undesirable value, the booster's excitation can be changed, effecting the proper voltage compensation to bring the kv-a. to a suitable value; thus a flexible voltage can be accomplished at both ends of the line, while fulfilling the important

requirement that suitable power factor correction may be effected.

In Fig. 29, receiving station C illustrates a wiring arrangement for a synchronous booster installation. Not only does the 11,000-volt distribution bus in station C have a flexible voltage, but so does that at the generating station, and in addition to this, the power factor of the transmission lines is under the control of the operator in station C. Furthermore, this operator is in a position to control the kv-a. of the synchronous condensers so that the power factor in each transmission line is maintained at such values as will secure suitable voltages at stations A and B, assuming that they are supplied from different lines.

Conclusion

1. The necessity of reactance in the circuits of modern systems is well recognized. Its importance has arisen with the growth of large systems, and is essential to prevent destruction by short circuits; to reduce within reasonable limits the size of oil switches, by diminishing the rupturing capacity which they must meet; etc. Transmission lines themselves, due to the spacing of conductors, furnish considerable reactance, but in addition to this, it is customary among operating companies to specify that the generators and transformers be built with considerable inherent reactance. To meet the requirements of some systems, even external reactances are supplied. Now, on the other hand, the development of industrial loads requires the extensive application of induction motors, whose exciting currents cause low power factor. Should these exciting currents be supplied over circuits involving considerable reactance, excessive voltage drops occur. Fortunately, synchronous machines can be located at the distribution centers to supply locally the necessary exciting currents, and by this means maintain uniform voltage regulation. It is not always economically practicable to locate synchronous generators or synchronous motors at the desired points. Hence, the synchronous condenser has been developed. This machine has come to fill an important place in the operation of transmission systems.

2. The combination of synchronous condenser and series booster offers an ideal method of voltage and power factor control. Not only can a flexible voltage be maintained at both ends of a transmission line, but an independent means of power factor control is secured for the transmission line itself, by which

a definite voltage control is established for some intermediate point in the transmission line. This certainly offers a very considerable advantage, in that it is frequently necessary to have a long transmission line with one or two intermediate stations.

3. A desirable feature of synchronous condensers on a high-voltage transmission system is that they offer protection against those voltage surges that arise due to a sudden loss of load, which might throw the generating stations on the unloaded transmission line with their generators on heavy field excitation. Under such a circumstance, due to the effect on the generators and transmission lines of the leading current set up by the charging current, a destructive voltage would occur. Over-voltage devices may be applied to the generators to give protection; however, with synchronous condensers on the receiving ends of the transmission lines, and each one equipped with an over-voltage device, an ideal solution of the problem is effected, since some of the synchronous condensers could be on the line at all times with their excitation under control through the desired range.

DISCUSSION ON "OPERATION OF TRANSMISSION LINES" (HAGOOD), SAN FRANCISCO, CAL., FEBRUARY 28, 1913.

Herbert W. Crozier: We are certainly much indebted to Mr. Hagood for the interesting paper we have had tonight, particularly the slides, which show great care in preparation.

I wish to ask him a question. With regard to the use of synchronous condensers, what do you find is the most satisfactory method? Suppose you have a large amount of power to deliver to consumers which would involve the use of synchronous motors driving direct-current generators,—would you prefer to make those synchronous motors just large enough to carry the load and have an additional machine synchronous to the condenser, or would you prefer to make the synchronous condensers large enough to take care of this regulation? That is the first question, and then the other is, what would you do if you had synchronous converters? That would be a different phase of the same subject.

Lee Hagood: With the synchronous machine, whether it is a generator or a motor, it can effect power factor correction and at the same time do work. I did not dwell very much on that point, because so many think that is the only way, economically, to use synchronous machinery for power factor correction. The ideal way of course is to let the synchronous machines do 70 per cent in kilowatts and about 70 per cent in wattless kilovolt-amperes, that is, rate these machines on a 70 per cent power factor basis. This applies to synchronous generators, frequency-changer sets, and synchronous motors. It is not always practical to locate these machines at the points where power factor correction is desired, hence the necessity for synchronous condensers.

The characteristics of a synchronous converter are such that its design does not lend itself to operation other than at 1.00 power factor at full load. It would not be safe, in general, to give operators instructions relative to using synchronous converters for power factor correction on light kilowatt loads, as a departure might lead to damage to the machine.

Herbert W. Crozier: Then I gather from your statement that the synchronous converter is fixed by the direct-current voltage, so any small amount of voltage control available would be fixed by the direct-current voltage, which presumably you would desire to keep constant.

Lee Hagood: That is one of the difficulties.

Herbert W. Crozier: But in regard to motor-generators driven by synchronous motors, if we take, for instance, a unit which would have a 1000-kw. direct-current machine, then the idea would be to purchase the motors considerably larger?

Lee Hagood: Yes.

Herbert W. Crozier: So as to take 70 per cent. You make the motor part 30 per cent greater?

Lee Hagood: Yes. It is not a good thing, in all cases, to put a voltage regulator on the motor, unless it is relatively large for its purpose. Even then the voltage regulator must be restricted in its operation so that no danger is incurred of the machine falling out of step by attempting to take a heavy kilowatt load on a weak field.

Robert Sibley: I notice that it has been announced that the Chicago, Milwaukee and St. Paul Railway will electrify some 500 miles (805 km.) of its line through Montana, and the proposal is to purchase power from the Great Falls Power Company at half a cent per kilowatt, the company agreeing to wholesale the power from the main transmission line. However, the power company also reserves the right to put in regulating devices at the receiving end. I would like to ask Mr. Hagood how such devices would differ in railroad work from such installations as he has shown us this evening.

Lee Hagood: As long as they are motor-generator sets it would be quite feasible to accomplish automatic voltage regulation provided the conditions were such that the machines would not have to run on weak fields, but if they are converters, I do not see how it would be practical.

Sometimes motor-generator sets are operated with fixed field excitation, or it is compounded so that as the load comes on the excitation is increased.

Herbert W. Crozier: One example of this phase control, that has worked out very successfully on the coast, is the Sierra and San Francisco Power Company, delivering power to the United Railroads. On their transmission line, 135 miles (217 km.) long, the same voltage is obtained at both ends of the line. The motor-generators are all 1500 kilowatts, I believe, and the regulation is obtained by controlling their fields. I believe they have now installed voltage regulators at a number of the stations and are getting very satisfactory voltage. This condition of course is one that does not always occur in regular commercial practise, because the power company has full control of a very large amount of synchronous apparatus at the receiving end. The ordinary condition is where there are many consumers taking current and using it any way they please, and it is up to the power company to make such regulation as it is able to. In such cases the synchronous condensers discussed tonight are apparently a very excellent feature. One thing that impressed me greatly was the fact that by the introduction of a synchronous condenser, results are obtained amounting to 25 to 30 per cent additional power delivered over the transmission lines, which certainly would appeal to our commercial friends as a considerable saving in capital expenditures necessary for transmission lines or for additional machinery. Heretofore we have been forced to buy generators to take care of the wattless current—and then more generators; and the use of the synchronous condenser in the substation is certainly a very valuable feature.

One thing that impressed me more than any other was the curve shown, if I remember the figures correctly, where 25 per cent more power could be delivered over the same transmission line with practically the same regulation.

A Member: Under what conditions, if any, is the use of synchronous condensers warranted by the decreased power loss due to the necessity for transmitting less wattless current through the line, apart from the question of voltage regulation? Another question. Is it possible to build synchronous condensers simply for regulating purposes so that for a given kv-a. capacity they are cheaper than a synchronous motor of the same capacity would be?

Lee Hagood: In regard to the first question, in the case of the 22,000-volt line (see Figs. 3 and 7 of the paper), at unity power factor the line losses are 7.5 per cent for 2500 kw. That includes the transformer loss—I mean the copper loss in the transformers. Since the losses vary as the square of the power factor we would get 15 per cent at 0.70 power factor. Now the synchronous condenser, to bring the power factor to 1.00, requires about 4 per cent on losses. That would give us a net under full-load conditions around 3.5 per cent. But not only that. We brought the power factor at the generators from 70 up to unity, and that meant that we reduced their core losses, armature and field copper losses. An approximate estimate of the saving is about 2½ per cent, giving a total net of 6 per cent. In the case of the 110,000-volt lines (see Figs. 22 and 23), the losses without the synchronous condenser—the efficiency of the line for delivering 30,000 kw., is 85 per cent, whereas with the condenser on the line the efficiency is 90 per cent. In this case the synchronous condensers have a loss of 1.3 per cent, giving a net saving of 3.7 per cent for the transmission line.

In regard to the design of the synchronous condensers, they can be designed with small air gaps, and with light bearings and bearing supports, since no mechanical load is carried; in view of these features they can be made cheaper than for the same rating as a generator or motor. Some day, perhaps, they may be built for much higher speeds and this will reduce their cost considerably.

Clarence L. Cory: I have been exceedingly interested in this paper, especially because not more than a year or so ago, one of the points, only touched upon in the paper, was gone into rather completely; and more than twelve years ago another point, which has been touched upon in the paper, was gone into carefully.

I will mention first the point that was considered only a short time ago.

We have heard this evening a very complete discussion of what the synchronous condenser or the synchronous motor, either very lightly loaded or doing perhaps 70 per cent of its

full-load work, may accomplish in the improvement of transmission conditions. A little over a year ago an investigation —a rather complete one—was made of the design of a 127-mi. (204-km.) steel tower transmission line having two three-phase circuits, maximum loss not to exceed about 6 per cent, as the power was purchased by the power user at the generating station and the tower line built by the power user, payment for the power to be made at the generating station. The amount of power required was to vary between 6000 and 10,000 kw., to be used primarily for induction motors, these induction motors to drive machinery for the crushing of about 20,000 tons of ore a day. Due to the consideration that other transmission lines were possibly to be interconnected, the voltage transmission was limited to about 80,000 volts. However, there were no taps for power along the line, nor was there more than the one generating station to be considered at that time.

The preliminary investigation indicated that 4/0 copper—the equivalent of that in stranded copper or aluminum, or aluminum of any sort—3/0 or 2/0, might be used. As has been shown this evening so very clearly, the problem in this case was not necessarily the very best possible regulation at the expense of other things; not necessarily the greatest efficiency in transmission at the expense of regulation; not necessarily the cheapest possible transmission system as regards cost of conductors at the expense either of efficiency or regulation or both. The power factor of the load was known to be somewhere around 80 per cent, due to the very large number of small induction motors. The frequency was fixed at 60 cycles, inasmuch as the generating station to be used, would be, in the future, one of a number.

Not by any means in the complete manner that has been developed in this paper, but by practically the same general principles, the general conclusion was reached that the installation of synchronous condensers at the receiving end would not only reduce the copper from 4/0 to 3/0, but it would improve the voltage regulation and at the same time increase the efficiency of transmission. A very careful analysis, using the complex quantity formula for the investigation of the power factor along the line from the generating station to the receiving station 127 miles distant, indicated that with the proper operation of these synchronous condensers doing anywhere from 50 to 70 per cent of their kilovolt-ampere capacity, it would be possible to get the best operating conditions.

Electrical energy in the form of direct current may, of course, be transmitted without introducing any of the undesirable effects due to the inductance or electrostatic capacity of the line. We start out with a given number of amperes at our generating station, using direct current, or theoretically with alternating current, with zero frequency, and we find absolutely the same

current at the receiving end, neglecting leakage; and the ideal of the transmission engineer with alternating-current power would be to produce a condition somewhat approximating that possible with direct current. We know that is not practically possible, at varying loads, because in the matter of transmission the direct current theoretically has an advantage over the alternating current. However, I can now see, having had this evening an opportunity to look at these curves, that there were instances where such problems might have been very directly solved by the proper use of these curves rather than by going through the rather complex computations that are otherwise necessary.

The other instance that I had in mind, occurring more than a decade ago, was a case where the installation of a comparatively small synchronous motor in a mine in California was made use of to improve the power factor of the load. One of the early transmission companies, fearing induction motors would lower the power factor, offered all consumers who would use their alternating current at approximately unity power factor, the advantage of receiving 920 watts for a horse power, whether real or apparent. A well-known engineer in San Francisco said, "Very good. If we can get 920 apparent watts for what we ordinarily pay for 746, we will see to it that we get 920 real watts,"—which was accomplished by the installation of a synchronous motor. This synchronous motor, at such times as the power was off—and in those days the transmission lines gave more trouble than they do today—was belted to a steam engine, and when the power was off the synchronous motor was operated as a generator and the mine was kept free from water. It was necessary to prevent the mine being flooded even if the transmitted power should be off only for a few hours. The result was that for a number of years the synchronous motor was ordinarily operated without doing any work whatever, and the power factor of the load was maintained at 100 per cent. The result was that the buyer of the power did receive 920 real watts, for which he only paid the price of 746 watts. I do not remember how many times that condenser or unloaded synchronous motor paid for itself every year, but I remember that it was used for a number of years.

I am only mentioning this because in this case the particular advantages of the operation of synchronous motors though lightly loaded or practically unloaded, were availed of to improve the conditions of transmission—improving the conditions in regard to both efficiency and regulation of voltage; and while I have not perhaps had an opportunity of fully studying the paper that has been presented this evening, I can see that in the first case mentioned the solution of that problem might have been made graphically from the curves presented by Mr. Hagood instead of being worked out in that one isolated case.

I would like to add this other point. Due to the careful investigations of Dr. Steinmetz's formulas for distributed capacity, also introducing the factor which it is possible to introduce in Dr. Steinmetz's formulas, namely, the amount of energy loss due to leakage between conductors, and going one step further than Dr. Steinmetz has gone, representing the results of some of his formulas graphically, it is possible to determine the power factor at any place you wish in your transmission line from your generating station to the point of delivery. If your line is 300 miles long it is only necessary to go through an elementary graphical construction as you would in determining stresses and strains in a structure, to ascertain what the power factor is at any point, simply substituting in the formula, whether the point under discussion is one mile from the generating station or 299 miles. So there we see the opportunities and the possibilities of further ascertaining the facts, and the desirability of introducing these synchronous condensers.

There is another point brought out that appeals to me especially. Not very many years ago it was generally understood that if we attempted to transmit power great distances where the charging current would be abnormal there was only one thing to do, namely, to reduce the frequency, if the voltage were maintained of sufficient magnitude to reduce the line losses. But one can see by viewing the curves that have been shown by Mr. Hagood that this is not necessarily true. Possibly we will be able to solve a great many of our problems at 60 cycles that we thought a few years ago could only be solved at one half that frequency or even one-third or one-sixth.

Not only are these few isolated instances that I have mentioned covered by the work that has been done by Mr. Hagood, but his work covers all other problems of a similar character.

L. P. Jorgensen: In substations where no motor power is required, the synchronous condenser is undoubtedly the most practical device that can be used successfully for voltage control; but in stations where the principal use for the power is to drive motors these motors should be so selected that part of them are synchronous and part induction. It is seldom possible, nor desirable, to have all motors on a transmission system of the synchronous type, as the starting requirements may be such as to exclude synchronous motors, and it may not be practical to provide direct current for excitation. Where large motors are to be dealt with, the extra outlay and complication for excitation does not amount to so much, and it is therefore of advantage to equip them with devices for voltage control to compensate for the lagging current of the smaller induction motors and other apparatus. The voltage in use at present on some of the largest transmission lines has reached the limit. This limit is set by the amount of corona loss permissible, so it is not possible to improve per cent of voltage drop by increasing the voltage, as this cannot be done. The critical voltage de-

pends upon size of conductors and elevation above sea level, and the limit of voltage has already been reached in several cases. The limit at sea level is somewhat above 120,000 volts where the amount of power is large enough to require conductors larger than 4/0. A few months ago I had occasion to visit a place and do some work in connection with a power transmission where 50,000 volts was the upper limit of transmission voltage, principally because of the high altitude, the average of which was 14,000 ft. (4270 m.). The lowest point on the line is the power house, located at 12,200 ft. (3720 m.) above sea level, and the highest substation is located at nearly 16,000 ft. (4880 m.) elevation. The line runs for the greater part of the distance of 120 mi. (193 km.) over a comparatively flat plateau of 14,000 ft. (4270 m.) elevation. This place is called the roof of the world, and is up in the Andes mountains in Peru. The load on this system is mostly motors driving copper mining machinery to the extent of about 10,000 h.p., requiring a conductor of No. 1 size cable. The motors are divided up between synchronous and induction in such a way that the power factor will be under complete control by means of automatic voltage regulators adjusting the excitation of the synchronous motors.

Herbert W. Crozier: I want to ask a question of Mr. Jorgensen. Did I understand you to say that 50,000 volts was the limit?

L. P. Jorgensen: Yes, because only 10,000 h.p. was to be transmitted. You could not afford to take larger than No. 0 cable, and at that diameter you cannot get above 50,000 volts.

J. P. Jollyman: One of the chief functions of the synchronous condenser in the ordinary transmission system is, as Mr. Hagood has pointed out, to help hold up the voltage. As the load on our system grows, frequently we run into conditions where excessive voltage drop limits the amount of the load which may be successfully carried at some point.

There is also another factor in the holding up of voltage which Mr. Hagood only touched on very briefly, but which to those of us who are connected with 60-cycle systems is a very important matter, and that is the charging current of the line, and its effect in balancing or neutralizing the lagging current due to the ordinary commercial load. The effect of this charging current is very considerable. We have at the present time in this vicinity a number of high-tension transmission voltages—60,000 and 100,000. At 60,000 volts the charging current amounts to about 18 kv-a. per mile. In other words, a company such as the one with which I am associated, operating some 1200 mi. (1930 km.) of 60,000-volt line, has a charging current of over 21,000 kv-a., and this is sufficient to raise 29,000 kw. of 0.80 power factor load to unity. That of itself has a very important effect in holding up the voltage of such a system. Now a 100,000-volt system has a very much higher charging current. As the voltage and the current go up your kilovolt-amperes go up. The charg-

ing current for a 100,000-volt line is about 52 kv-a. per mile. In other words, a 300-mi. (483-km.) line would have some 15,000 or over 15,000 kv-a. wattless leading current component, which would assist in balancing the bad power factor of the ordinary commercial load. This wattless component on 300 miles of 100,000-volt line would balance 21,000 kw. at 0.80 power factor load, bringing it up to unity. I believe that the charging current which, as you see, is no small amount on systems which are operating, has a very important effect in helping to hold up the excitation. The excitation on a transmission system is somewhat analogous to the mechanical condition of the cantilever beam. If the excitation is supplied entirely at the generating station it is somewhat analogous to a cantilever beam supported at one end and loaded at the other. Such a beam must necessarily sag at the loaded end. The voltage cannot be anything but lower at the receiving end where you have purely load and are supplying no excitation in the way of synchronous machinery. The variations in voltage with the variations in load are somewhat analogous to the variations in the sag of such a beam with a varying load. To steady that beam you may supply some support at the free end. In other words, you may apply some synchronous machinery at the receiving end. It is obvious that you may *steady the variations* in the deflections of that beam with very much less support than would be required if you wanted to raise the beam up to the same level that it was held at the fixed end; and that is, as near as I can suggest, a mechanical analogy to the transmission problem in the operation of synchronous condensers. It is obvious that a beam supported at both ends will have less sag if it is loaded uniformly than if it is supported at one end as is the case in the transmission system. If you have synchronous apparatus at both ends the voltage drop will be less throughout the system. I think it would be well for any one having to do with the design of transmission systems to consider always the effect of their charging current, and to bear in mind that it is a very considerable amount, very closely approximating 18 kv-a. per mile for 60,000 volts at 60 cycles; and 52 kv-a. per mile for 100,000 volts and 60 cycles. There have been some transmission systems projected recently where the charging current is going to prove a very serious problem to handle properly. My own opinion in the matter is that you should not ordinarily attempt to operate a single transmission circuit with generators which are less in capacity than the charging current. In the system on which we are working at the present time the kv-a. capacity of a generator is approximately double the charging current on the line, and I anticipate that we will not be very much bothered by variations in load or bringing the empty line up to voltage.

Herbert W. Crozier: Mr. Jollyman apparently has given this matter of the charging current a very considerable amount of thought. The point I want to draw attention to in connection

with the use of synchronous condensers for the regulation of the line is the matter of safety. We all know that the loss of load due to excitation and opening of circuit breakers and other things causes a very considerable rise of voltage at the substations; and the use of the synchronous condenser controlled by the automatic voltage regulator is certainly an element of safety, because there is something there which will make a change in the conditions in the end, assuming of course that the synchronous condenser is so installed as to remain connected to the transmission line. I remember two or three cases where very disastrous results occurred, due to the opening of the end of a transmission line, causing the wrecking of lightning arresters and general destruction of such apparatus as still remained connected.

L. N. Peart: We have a 60,000-volt line approximately 200 mi. (322 km.) long, and I can confirm some of Mr. Jollyman's remarks very strongly, because I have just made some experiments on the power factors of this line, and also some corrections obtained by using some turbines at one end of the line as synchronous condensers. We have about 200 miles of 60,000-volt line, fed at one end by a hydroelectric station, and at the other end by a steam auxiliary. The hydroelectric end is 16,000 kw. capacity; the steam end is about 8000 kw.; and close to the steam end at the outer end of the line we have the oil fields, which furnish a very highly inductive load. The power factor at the oil fields loads is approximately 70 per cent, and when we first started the transmission line the power factor of the transmission line at the power house was 62 per cent leading. That was before we had much oil field business. As the oil field business came on—and I might say that the power factor of the oil field load is not much better than between 60 and 70 per cent—it never gets over 70—the power factor at the transmission end at the power house gradually approached unity, and at present, it is very close to that. Now operating the turbines in Bakersfield at 8000 kw., allowing them to float on the line with a little steam and adjusting the exciting current, we are able to keep the voltage regulation of the system very nearly constant, that is, we can hold the voltage in Bakersfield and at the power house end practically the same, with a rise of voltage in the middle of the line of about 8 or 10 per cent. Recently, due to the failure of some of the hydroelectric machinery at the generating end, the water end, it was necessary to carry the entire load from the Bakersfield end. You will appreciate that without any feeder voltage regulators on the system, the step-down transformer stations are connected through the proper taps to the line so that we get the proper voltage grading; in other words, near the power house the transformers are on a higher tap and gradually decrease down the line to take care of transmission drop. Feeding from the steam end, matters were reversed, and it was a question whether we were going to get any voltage regulation; but operating the hydroelectric generators as synchronous condensers,

and feeding from the Bakersfield end with the steam generating machinery, we were able to keep suitable voltages at all points. That, I think, furnishes a very good illustration of Mr. Hagood's point.

J. P. Francis: There is one other point in the operation of a synchronous motor as a condenser that it is well to consider, and that is, that by limiting the range of the exciter voltage, so that when the voltage of the transmission line is too high the regulator is lowering the voltage of the motor, the excitation of the synchronous motor will not be reduced too greatly, causing the machine to fall out of step if the load increases suddenly. Also, the upper limit of the exciter voltage should not be high enough to burn the regulator contacts when the synchronous machine is boosting.

R. C. Powell: Mr. Jollyman mentioned that the charging current in the line should be taken into consideration. The point is, as I understand it, that the charging current will help out the generators but not the line.

Clarence L. Cory: It ought to help out both.

R. C. Powell: That is, with a simple line.

H. Y. Hall: I think Mr. Jollyman's point was more in respect to regulation. There is no question but that the charging current of the line will help out the regulation.

R. C. Powell: I don't believe I can agree with you, for the reason that the regulation will be the difference between the voltage and no-load voltage. At no-load the voltage at the receiving end will be higher than at the transmitting end, due to the charging current. Now if the load comes on, the charging current is constant, and the voltage rise due to the charging current is constant, so where you would start with 100,000 volts with no-load and get 120,000 at the receiving end, at full load you would have 20,000 drop, and you would have 100,000 at each end; but your regulation is the same.

J. P. Jollyman: I would say that the principal effect on the distributing system is naturally the improvement of the power factor of the load that the generators carry. The charging current is roughly one-half as effective in helping out the line as would be a synchronous condenser at the receiving end. The charging current is distributed, but it is not far, in general, from the effect of either the equivalent leading current load at the center of the line, or one-half of the load at the extreme end of the line. You will frequently find that a transmission system which starts out purely as a transmission affair, and transmits a very large percentage of its power over practically its entire length, grows into a system in which more or less load is taken off along the line; and in that case the charging current to a certain extent neutralizes the lagging current of the load, the load being somewhat distributed, and the charging current being entirely distributed. The principal effect of the charging current, as I stated, is an improvement in the

generator power factor, which is a very important matter; and it is perhaps in its effect on the efficiency of transmission roughly half as effective as a concentrated synchronous condenser of the same capacity at the load point.

A Member: I would like to ask Mr. Jollyman if the value he gave of 18 kv-a. for a 60,000-volt line and 52 kv-a. for 100,000 volts, has a certain regard for the spacing, and cannot that be varied by altering the spacing?

J. P. Jollyman: I think if you will consider the practical cases of transmission at 60,000 volts you will find that the spacing is usually, in modern construction, about five or six ft. (1.5 to 1.8 m.), and for 100,000 volts the spacing is nine or ten ft. (2.7 to 3 m.), and is frequently in a vertical plane, which means that the average spacing of the phases is about one and one-third times the distance between the two wires. I have found by plotting the values of the charging current in relation to the ratio of the diameter of the wire to the spacing, that the change in the value of the charging current over the range of actual construction such as is generally employed by operating companies, is very small. If I remember correctly, the charging current per mile (1.6093 km.) for 10,000 volts over the range of construction ordinarily employed varies from about 0.028 of an ampere to about 0.031. The values that I gave were based on 0.03 of an ampere for 10,000 volts per mile. The charging current does not change very rapidly over the range of spacings, with the size of wire ordinarily employed. If you have a rather small spacing and very large conductors it would be a little different from what it would be if you had large spacings and very small conductors; but the change is really so small, and there are so many other things that enter into the exact determination of this value, that these figures are sufficiently accurate for ordinary calculation. You would not select the size of a generator down to anything smaller than 500 kilowatts, and these values will give you the charging current within a few hundred kilovolt-amperes of the actual value.

A paper presented at the 281st meeting of the American Institute of Electrical Engineers, New York, March 14, 1913.

Copyright 1913. By A. I. E. E.

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY

BY C. L. FORTESCUE AND S. W. FARNSWORTH

I. Introduction

The breakdown strength of air between conductors or terminals of different sizes and shapes when expressed in volts per cm. of separation, is a very variable value and of little significance. The great variation is not due to any difference in the strength of air, for that is a physical constant, which, according to the results of many able investigators, has a value of between 30 and 38 kilovolts (maximum value) per cm. The variation is due rather to the influence of such factors as the shape and size of the terminals or conductors, and also to the position and potentials of these bodies relative to neighboring bodies. The case of comparative breakdown distances between spheres and needle points for a given voltage, furnishes an excellent illustration of this point. For example, with 25 cm. between spheres 25 cm. in diameter, the air breaks down at 260,000 volts, whereas, it requires 67.3 cm. to withstand the same voltage between needle points. In the first case the volts per cm. are 10,400, whereas, in the second case the volts per cm. are 3870 (9800 volts per inch). Looking at air as a means of insulating a potential of 260,000 volts, it is evident that it serves much more efficiently in the case of the spheres than in the case of the needle points. When serving at its maximum efficiency, it will stand from 30 to 38 kilovolts (maximum) per cm., and for the purposes of this paper, the lower value will be assumed.

In most practical applications of air as an insulator, the problem is complicated by the presence of other dielectric media

having a higher specific inductive capacity than that of air. There is, in general, a false conception of the parts played by the two media, namely, the solid dielectric and air, in performing their functions in the insulator. With increased voltage, the part the air plays becomes more and more important and at present-day voltages should no longer be disregarded. While the breakdown voltage of air alone, as expressed in volts per cm., is a very variable quantity, the breakdown voltage of air over the surface of a solid dielectric when expressed in the same terms (a value commonly called "creepage" voltage) is still more variable and of even less significance.

As there are ways, as illustrated above, of using air alone more efficiently than is ordinarily done, so are there ways of using the combination of air and a solid dielectric more efficiently. It is the purpose of this paper to show the conditions that determine the disruptive strength of an air path along the

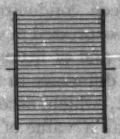


FIG. 1

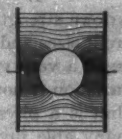


FIG. 2

surface of a solid dielectric of higher specific inductive capacity, and what steps must be taken to insure the most efficient use of the two dielectrics in combination.

II. The Electric Field in the Presence of Solid Dielectrics

The effect of introducing an insulating body into the static field between two conductors is to increase the stress in the air path at the surface of the conductor and at the surface of the insulating body, unless certain laws governing the proper shaping of the body, which will be stated later, are observed. This statement may be easily verified experimentally, by placing a glass sphere in the electrostatic field between two parallel plates maintained at different potentials. If the static field is intense enough, the introduction of the sphere will cause corona to form at the surface of the sphere and at the contiguous parts of the two plates; the air between the plates will consequently break

down at a much lower voltage than if the glass sphere were absent.

Fig. 1 shows the condition of the static field before the introduction of the glass ball. Fig. 2 gives an idea of the condition of the field after the glass ball has been introduced. It will be seen that the lines of force concentrate in the glass ball and are more dense at its surface and at the portion of the surface of the two plates nearest the ball than anywhere else.

A close analogy to the action which takes place when the glass sphere is introduced into the electric field is obtained by placing a steel ball in the magnetic field between two large poles of opposite polarity. In this case the field may be mapped out with iron filings.

Fig. 3 shows a method of plotting the equipotential surfaces of the current flow between two conductors which are similar to the equipotential surfaces in the electric field between terminals of similar shape. To obtain the equipotential surfaces or current flow, current is passed between the two terminal plates suspended in a conducting liquid. Between the plates is suspended a metal ball. An insulated exploring lead is taken from any given point on the calibrated resistance placed across the supply voltage and carried into the liquid, where it terminates in an uninsulated point. The needle is moved about, always keeping the galvanometer zero, thus indicating the location of points of the same potential as the chosen point on the resistance. The movement of the exploring needle is recorded by means of a pantograph.

Fig. 4 shows one of many charts taken according to the method shown in Fig. 3. The bath used in this case was salt water, and the two terminal electrodes a cylindrical rod and a torus ring in the relative positions indicated. The wavy lines show the observed equipotential surfaces. The small circles indicate points of definite observed potential. The smooth lines show theoretical equipotential surfaces of indicated potential for the given terminals. Having obtained the equipotential surfaces, the lines of flow may be drawn in at right angles to them. If in Fig. 3 the sphere should be steel and the bath mercury, since the conductivity of iron is about ten times that of mercury, the field obtained would resemble very closely the field for the glass sphere in air, the specific inductive capacity of glass being about eight.

The conditions that exist at the surface of the dielectric of

high specific inductive capacity in a field of force in air are brought about as follows: A given difference of potential will cause a very much greater electric flux in the solid dielectric

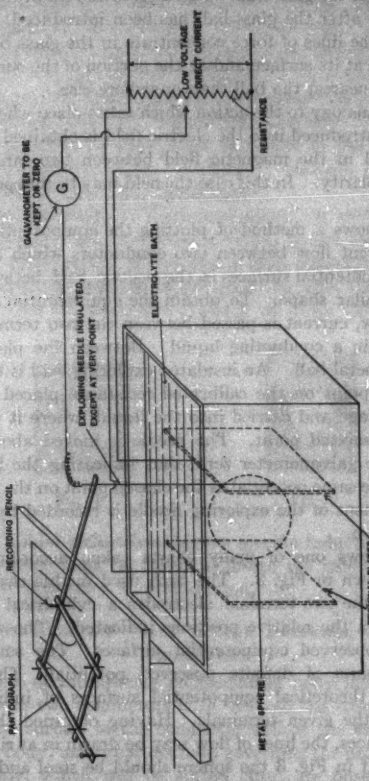


FIG. 3.

than in air. At the surface of separation of the air and the solid, the tangential component of the intensity must be the same in the air as in the solid. Since it requires K times the force to produce the same dielectric flux in the air as in the solid, where K

is the value of the specific inductive capacity of the solid dielectric, the component of intensity in the air normal to the surface will be K times that in the solid dielectric. The intensity at each point of the surface of separation is increased from what it was

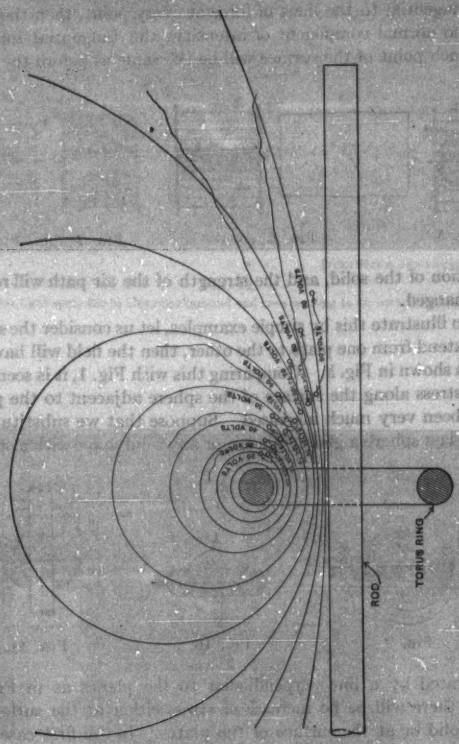


FIG. 4.

before the introduction of the dielectric and is more nearly normal to the surface. If the solid body extends from one conductor to the other, we may have a condition in which the tangential component of the intensity will be nearly uniform, but

the maximum intensity being in a direction more nearly normal to the surface than before the introduction of the solid, its value is greater at every point. The air path along the surface is, therefore, weaker than before the introduction of the dielectric. If, however, we form the dielectric so that its surface is tangential to the lines of force at every point, then there will be no normal component of intensity; the tangential intensity at each point of the surface will be the same as before the intro-

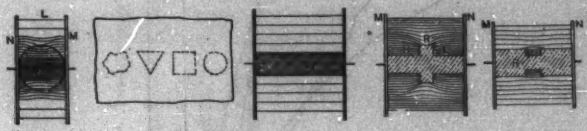


FIG. 5 FIG. 6 FIG. 7 FIG. 8

duction of the solid, and the strength of the air path will remain unchanged.

To illustrate this by simple examples, let us consider the sphere to extend from one plate to the other, then the field will have the form shown in Fig. 5. Comparing this with Fig. 1, it is seen that the stress along the surface of the sphere adjacent to the plates has been very much increased. Suppose that we substitute for the glass sphere a glass cylinder, or any solid shape with a surface

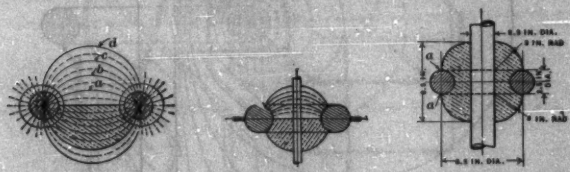


FIG. 9 FIG. 10 FIG. 11

generated by a line perpendicular to the planes as in Fig. 6, then there will be no increase of stress either at the surface of the solid or at the surface of the plates. In the first case, the introduction of the solid has decreased the breakdown strength by a large amount, but in the second case the strength is unimpaired by the introduction of the solid. Fig. 7 shows two planes, M and N, having a piece of insulating material extending continuously between them with a projection in the middle such as

[FORTESCUE AND FARNSWORTH]

FIG. 12
(Circular light spots due to shiny background and have nothing to do with the discharge.)

[FORTESCUE AND FARNSWORTH]

FIG. 21
(Circular light spots due to shiny background and have nothing to do with the discharge.)

is commonly employed to give increased "creepage" distance. In the light of the previous explanation, it is seen that the air in the path *HL* will be stressed to a higher value than if the projection *R* were not present. That is to say, the very thing which is ordinarily sought for, namely, an increased distance over the surface, is shown to be detrimental in this case rather than beneficial. The higher the specific inductive capacity of the material, the more detrimental is the projection.

Should a groove be placed in the insulating material as in Fig. 8, another very poor condition is obtained, as the air at *R* will be stressed beyond its limit at a comparatively small difference of potential between *M* and *N*.

The cross-hatched portion of the lower half of Fig. 9 shows how the insulation would have to be shaped to insulate two parallel wires with a maximum efficiency. The surface could be made to conform to any one of several flow lines, *a*, *b*, *c*, etc.

III. Practical Application of Theory with Results of Tests

Fig. 10 shows a means of insulating a terminal rod passing through a casing. Experimental pieces of this design were made up to dimensions shown in Fig. 11. The material used was a mixture of shellac, whiting and various gums. The bushing was cast in an accurately machined mould. A maximum breakdown of 145 kv., effective value, was obtained, and when good care was taken to have a clean surface, the breakdowns were seldom less than 135 kv.

Fig. 12 shows a breakdown at 137 kv. on one of these bushings and it will be noticed that there are no evidences of corona at any point of the surface.

Fig. 13 shows the calculated intensity curve for the surface path. Assuming a maximum allowable intensity of 19.7 kv. per cm. (50 kv. per in.), effective value, at the points of highest intensity which are at the surfaces of the ring and rod, by integrating the area under the curve, we obtain the voltage necessary to break down the path, which on the above assumptions is 142 kv. It will be noted from the curve that the minimum intensity is 9.1 kv. per cm. (23.2 kv. per in.) or slightly less than half the maximum value. The distance over the surface is 11.9 cm. (4.7 in.) so the average volts per cm. for a breakdown voltage of 145,000 is 12.2 (31 kv. per in.).

The dimensions of ring and rod chosen were such as to give

a maximum breakdown voltage over the surface for a mean diameter of a torus ring of 21.6cm. (8.5in.). The surface of the solid was made to conform to the flow lines, leaving the torus ring on line *a*, Fig. 11. Any other set of flow lines might have been chosen. Had a set been chosen leaving outside of lines *a*, there would have been difficulty in casting the bushing due to the back draft on the mold. If a set of lines had been chosen leaving inside of lines *a*, there would have been a pocket to catch dirt.

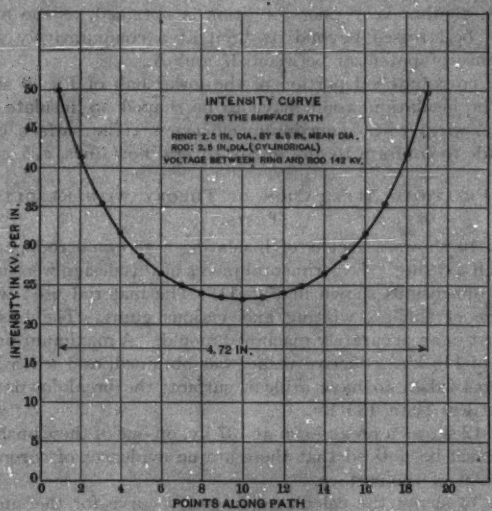


FIG. 13

The law of similar fields applies to these cases, so if all the dimensions of Fig. 11 be doubled, the breakdown voltage should be doubled.

As a matter of interest, the approximate intensities existing through the insulating material along the line of minimum separation between ring and rod were calculated, and are given in Fig. 14, considering a voltage of 142,000 applied. The intensity is seen to be less at the ring than at the rod, and for the given voltage, the intensity at the rod is 46 kv. per cm. (117 kv. per in.)

effective value. Ordinary insulating material should be capable of standing this voltage without being unduly stressed. This is the more evident when we consider that air itself is capable of standing 21 to 27 kv. per cm. (54 to 68 kv. per in.)

The above analysis of the intensities in the solid dielectric suggests that to find the real strength of insulating materials, some form of terminals should be used which will permit calculation of the stress at the point of maximum intensity when breakdown occurs.

In order that the great gain which can be made by properly designing the surface of the solid dielectric may be more evident,

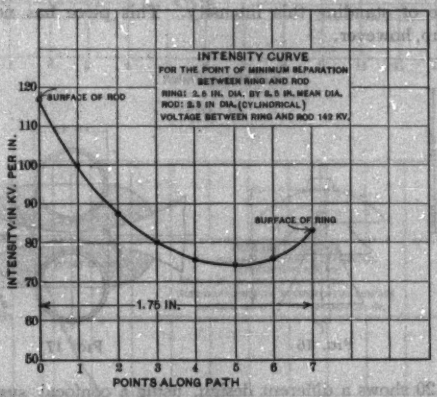


FIG. 14

attention is called to the breakdown over the surface of a former standard transformer bushing and an ordinary line insulator. Fig. 15 shows the transformer bushing which was formerly a standard for 66,000-volt work and which would flash over its 81½ cm. (32 in.) of surface at a voltage of about 145,000. In the bushing shown in Fig. 13, a distance of 11.9 cm. (4.7 in.) breaks down only when this same voltage is reached. Fig. 16 shows an ordinary line insulator having a surface distance of 63.5 cm. (25 in.) which breaks down at 119,000 volts.

By changing the shape of the terminals it is possible to design a bushing which will have a higher average intensity over the sur-

face before breakdown of the air will occur. Fig. 17 shows an arrangement similar to that of Fig. 11, which accomplishes this. Allowing the same mean diameter of torus ring, 21.5 cm. (8½ in.), as used in Fig. 11, and the same maximum intensity in the air, we see from Fig. 18 that the calculated breakdown voltage will be 181 kv. The minimum intensity is 13.2 kv. per cm. (33.5 kv. per in.) as against 9.15 kv. per cm. (23.2 kv. per in.) for the bushing shown in Fig. 11. Fig. 19 shows the calculated maximum intensities in the solid, which are 179 kv. per cm. effective value, (455 kv. per in.) at the surface of the rod. Judging from our tests, it seems reasonable to expect that what are ordinarily considered as good insulating materials, will be capable of standing this intensity. This piece has not been made up, however.

FIG. 15

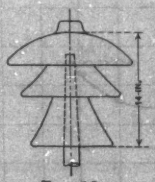


FIG. 16

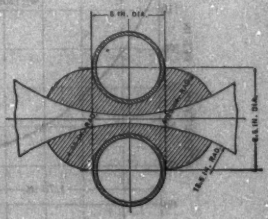


FIG. 17

Fig. 20 shows a different design, using a confocal system of ellipsoids and hyperboloids of revolution, having foci which are 5.08 cm. (2.0 in.) apart. A piece was turned out of hard rubber to the given dimensions and the average breakdowns over the surface have been above 160,000 volts; thus giving an average of 9.4 kv. per cm. (23,900 volts per in.) for a surface distance of 17.0 cm. (6.7 in.). These values are striking when compared with the breakdown voltage of 145,000 volts for 81½ cm. of surface of the bushing shown in Fig. 15. In that case the average kilovolts per cm. are 1.78 (4.54 kv. per in.).

This piece was placed where it would collect dust and dirt such as it would be likely to in indoor service and was tested after three months. It showed no deterioration in breakdown strength, even with this heavy coating of dust.

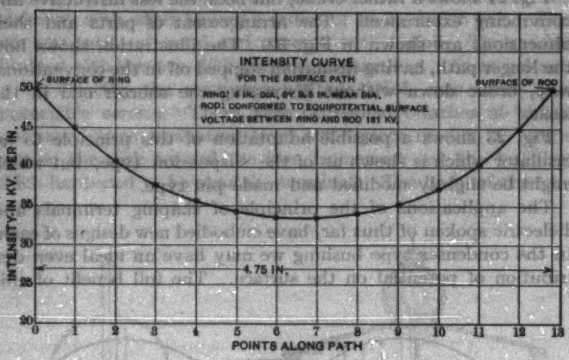

INTENSITY CURVE
FOR THE SURFACE PATH
RING: 6 IN. DIA. BY 5.5 IN. MEAN DIA.
ROD: CONFORMED TO EQUIPOTENTIAL SURFACE
VOLTAGE BETWEEN RING AND ROD 181 KV.
SURFACE OF RING
SURFACE OF ROD
4.75 IN.
INTENSITY-IN KV. PER IN.
POINTS ALONG PATH

FIG. 18

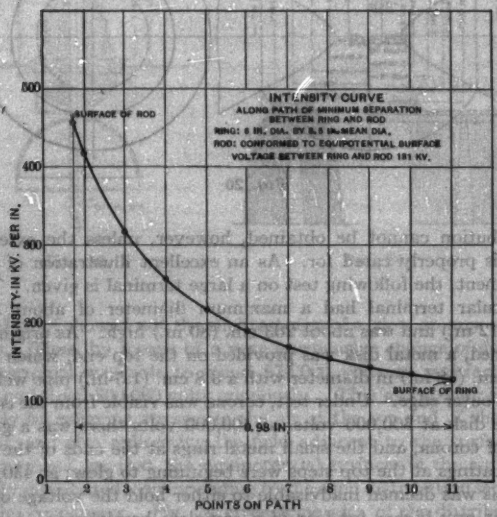

INTENSITY CURVE
ALONG PATH OF MINIMUM SEPARATION
BETWEEN RING AND ROD
RING: 6 IN. DIA. BY 5.5 IN. MEAN DIA.
ROD: CONFORMED TO EQUIPOTENTIAL SURFACE
VOLTAGE BETWEEN RING AND ROD 181 KV.
SURFACE OF ROD
SURFACE OF RING
0.98 IN.
INTENSITY-IN KV. PER IN.
POINTS ON PATH

FIG. 19

Fig. 21 shows a rather crude, but none the less instructive and convincing experiment. The arrangement of parts and their dimensions are shown in Fig. 22. The illustration shows how the longer path, having insulation stepped off in the conventional way, broke down without distressing the shorter end in the least.

Fig. 23 shows a possible adaptation of this principle to an insulator which is shown as of the suspension type, but which might be slightly modified and made pin type.

The applications of the principle of shaping terminals and dielectric spoken of thus far, have embodied new designs of each. In the condenser type bushing we may have an ideal even distribution of potential on the surface. The full benefit of this

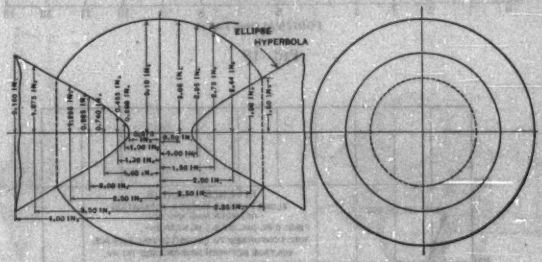


Fig. 20

distribution cannot be obtained, however, unless the external field is properly cared for. As an excellent illustration of this statement, the following test on a large terminal is given. This particular terminal had a maximum diameter of about 30.5 cm. (12 in.) and was about 203 cm. (80 in.) high. As originally designed, a metal disk was provided on the top end, which was 40.6 cm. (18 in.) in diameter with a 3.8 cm. (1.5-in.) pipe welded on its outer edge. Under test, corona was visible from the edges of the disk at 300,000 volts; at 400,000 volts there was a great deal of corona, and the small metal rings at the ends of the tinfoil coatings at the top steps were beginning to glow; at 430,000 volts is was deemed inadvisable to either hold the voltage or to raise it any higher for fear of a complete breakdown. A new disk was designed for the top of the terminal and the dimensions

selected were 152.5 cm. (60 in.) diameter and 30.5 cm. (12 in.) thickness, with edges having a radius of 15.25 cm. (6 in.). The disk was made of wood and covered with tinfoil. The results obtained with this new disk were rather startling. At no voltage up to 575,000, the maximum voltage tried, was there any appreciable corona. There were occasional bunches of bluish fan-shaped haze emanating from some piece of dirt or rough spot on the disk toward the iron framework of the building which happened to be near the terminal. The body of the ter-

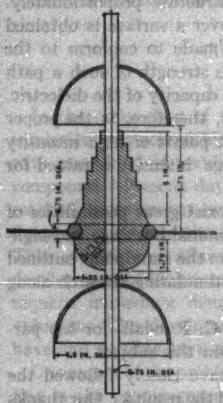


Fig. 22.

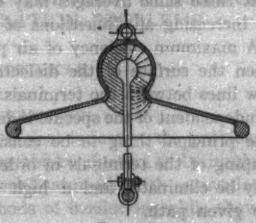


Fig. 23.

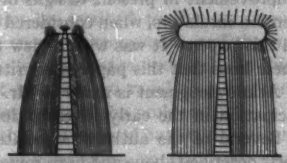


Fig. 24.

minal itself showed not the slightest sign of a glow on any of the steps. Thus, by means of a very inexpensive change of design, the terminal was able to stand 575,000 volts as satisfactorily as it had stood 300,000 volts previously. This was accomplished simply by relieving stresses in the air at the top end of the terminal, and also redirecting the field adjacent to the surface of the terminal, so that the equipotential surfaces in the air were evenly distributed, corresponding to the even distribution secured by the condensers. Fig. 24 gives some idea of the distribution of the field under the two conditions.

IV. Summary and Conclusions

We have given, in this paper, a new conception of the functions which air and a solid dielectric perform when used in combination for insulating purposes. Based on this conception, a large number of tests have been made under commercial conditions, which show that it is possible to use air more efficiently than has been customary in the past. Breakdowns of an air path over a surface have been obtained which average as high as 9.4 kv. per cm., effective value, (23,900 volts per in.) over a distance of 17.0 cm. (6.7 in.). The conditions of design are such that these same averages may be maintained at any voltage, by increasing all dimensions of the structure proportionately.

A maximum efficiency of air path over a surface is obtained when the surface of the dielectric is made to conform to the flow lines between the terminals. The strength of such a path is independent of the specific inductive capacity of the dielectric. The principal thing to be considered, therefore, is the proper shaping of the terminals in order that points of high intensity may be eliminated and a high average intensity obtained for the given path.

It seems to the authors that there exist great possibilities of improvement in present designs of terminal bushings and high-tension insulators, when considered from the standpoint outlined in this paper. It was with a view to stimulating research along these lines that this paper was written.

Acknowledgment is made to Mr. K. C. Randall, for his participation in the early investigations on this subject.

Several of the authors' associates have closely followed the tests described above and have reviewed the results. Our thanks are due to Messrs. H. J. Ryan, C. F. Scott, L. W. Chubb, J. A. Sandford, Jr., H. B. Smith, B. G. Lamme, H. E. Clifford and C. E. Skinner for the interest they have taken in this investigation.

A paper presented at the 281st meeting of the American Institute of Electrical Engineers, New York, March 14, 1913.

Copyright, 1913, By A. I. E. E.

THE APPLICATION OF A THEOREM OF ELECTROSTATICS TO INSULATION PROBLEMS

BY C. FORTESCUE

I. Introduction

In the early days of the electrical industry, the problem of insulation was solved by taping the conductors to be insulated with some kind of textile material saturated with an insulating compound. Present day methods of insulation, while showing marked improvement over those in the past, still retain the influence of early tradition, and are largely based on rule of thumb. This condition of affairs may be ascribed to the very rapid development of high-tension transmission systems, and the consequent immediate demand for apparatus insulated for high voltages. The development has been so rapid that engineers have had no time for a proper study of the problem.

One aspect of the problem that has received but little consideration is the proper grouping of conductors, so that they shall assist in insulating one another. To illustrate this idea by an example that will be familiar to everyone, consider two spheres 25 cm. in diameter and 25 cm. apart, at potentials + 200,000 and − 200,000 and a small thin disk of conducting material connected to ground and placed near the spheres. The disk may be placed in a number of positions in which it is insulated from both of the spheres, but there is only one set of positions in which it will cause no disturbance of the electric field, namely, those lying in the zero potential surface or plane of symmetry midway between the two spheres. If one of the spheres be removed, the balance will be disturbed and the remaining sphere will discharge to the disk. Thus the presence of the sphere of potential + 200,000 has served to insulate the sphere of potential − 200,000 from the

grounded disk. Very thin wires may be brought into the field of the two spheres and maintained at a difference of potential many times larger than their normal disruptive voltage.

In such cases as these the ordinary rules of procedure followed in insulation methods are seemingly violated. Thus sharp edges and fine wires are more effectively insulated than thick rounded edges and large wires. In practical work, conductors usually have edges where the intensity becomes high, and therefore, if by some method, these sharp edges can be insulated as effectively as large rounded edges, a valuable advantage will have been gained.

The object of this paper is to emphasize a principle of electrostatic theory by which the individual units of a system of conductors may be arranged to protect one another. The statement of the principle and several illustrations are given in Section II following.

II. Statement of Principle of Electrostatic Theory with Illustrations

If a region in any particular electric field be isolated or cut out by any number of closed surfaces, then the electric field in this region will remain unchanged, whatever change may take place in the external electric field, if the potentials at all points on the enclosing surfaces are maintained at their original values.

It follows from the above that the intensity due to the surface distribution will, at each point of the region, be the same as that of the assumed electric field. The potential in such a region will be unaffected by any change in position or electrification of external bodies, since it is uniquely determined by the surface potential distribution which remains unchanged.

It is also obvious from this principle that two or more regions, completely separated from one another by any number of surfaces, may each have a different electric field, if at every point of the dividing surface or surfaces between any two of the regions, the fields in these regions have the same potential.

The truth of the principle just stated is almost self-evident, for it is known that when the potentials of a system of conductors are given, there is only one possible solution of the electric field consistent with the proper conditions. If, therefore, a solution be known that will give the same potential at each point of the bounding surfaces of a given region, as the assigned potentials, then this must be the only possible solution. It is not so easy

to see that the field within the region is independent of any external influences. This may be deduced from the fact that, in order to produce a potential within the region, an external system must also produce a potential at each point of the surfaces, and, since the potentials at the surfaces are maintained constant, the effect of external bodies within the region must be zero. Changes in the external electric field have the effect, however, of altering the charges at each point of the surface. In other words, the effect of any change in the external system is to produce a change in the capacity of the system of charged bodies at the surfaces of the region, in such a way that there is a change in the surface charges, the potentials remaining constant, of such a nature as to completely annul the effect within the region of the change in the external system.

The analytic theorem upon which this principle is based may be found in Maxwell's "Electricity and Magnetism," 1904 edition page 136, Article 99.(b). A more general proof af the same theorem is given in Kelvin and Tait "Treatise on Natural Philosophy," 1903 edition, Vol. 1, Chapter 1, Appendix A (c). A full discussion of Green's problem, which has some bearing on the above principle, may be found in Volume 2 of the same work, Articles 499 to 508 inclusive. Reference may also be made to Jean's "Electricity and Magnetism," Articles 186, 187 and 188, and to Webster's "The Theory of Electricity and Magnetism," the last paragraph of Article 86.

A few simple illustrations of electric fields produced in accordance with this principle may serve to give a more vivid conception of its use.

Consider two parallel plane conductors, forming two portions of the surface of a solid dielectric. To produce within the body a uniform field corresponding to that between two infinite parallel plates having the same potentials as the two conductors, all that is necessary is to produce at each point of the surface of the dielectric a potential equal to that of the uniform field at that point. The whole surface of the dielectric might be considered as mapped out in equi-potential contour lines infinitely close together and each line may be imagined to become a conductor which will be supposed to be connected to an external source of the proper potential.

A dielectric sphere in a uniform field furnishes an interesting application of this principle. If the potential of the field be $V = R\,x$, and if the center of the sphere be at the origin and its

radius be a, any distortion of the field due to the difference in specific inductive capacity of the sphere from air may be prevented by maintaining, at the surface of the sphere, a potential distribution,

$$V_s = R\,a \cos\theta$$

Under this condition, the potential both inside and outside the sphere will be,

$$V = R\,x$$

Without the surface distribution, the potential inside the sphere would be,

$$V_1 = \frac{3}{K+2}\,R\,x$$

and that outside the sphere would be,

$$V_0 = R\,x\left\{1 - \frac{K-1}{K+2}\left(\frac{a}{r}\right)^3\right\}$$

The maximum value of the intensity at the surface of the sphere in the air would be,

$$R_0 = \frac{3\,K}{K+2}\,R$$

Thus if $K = 4$, $R_0 = 2\,R$. The intensity therefore has been doubled at the maximum point by the introduction of the sphere.

It is interesting to find the surface distribution of electricity produced on the sphere by the potential distribution, V_s over the surface. Let V_2 be the internal potential due to this surface distribution of electricity. Then

$$V_2 = R\,x - V_1$$

$$= \frac{K-1}{K+2}\,R\,x$$

The surface density required to produce this internal potential is

$$S = \frac{3\,(K-1)}{4\,\pi\,(K+2)}\,R\cos\theta$$

The external potential due to this surface density will be

$$V_3 = \left(\frac{a}{r}\right)^3 \frac{K-1}{K+2}\,R\,a\cos\theta$$

or since

$$r \cos \theta = x$$

$$V_2 = \left(\frac{a}{r}\right)^3 \frac{K-1}{K+2} R x$$

and this when added to V_0, the external potential obtained without the potential distribution, gives the potential outside the sphere when the surface potential distribution is determined according to the principle. That is,

$$V_0 + V_2 = V = R x$$

A section of the equipotential surfaces of the electric field in the neighborhood of a dielectric sphere ($K = 4$) in a uniform field, with and without the proper potential distribution, is shown in Figs. 1 and 2.

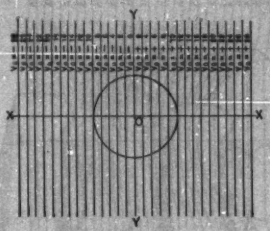


FIG. 1—SECTION BY PLANE PASSING THROUGH AXIS OF X OF EQUIPOTENTIAL SURFACES OF DIELECTRIC SPHERE IN A UNIFORM ELECTROSTATIC FIELD.

The sphere has the proper potential distribution over its surface to insure no distortion of the field.

Cylindrical conducting bodies and insulating structures are of common occurrence in practical problems. Suppose it be required to insulate a short external cylinder from a long internal concentric cylinder. A line may be drawn from the ends of the external cylinder to the nearest point on the ends of the inner cylinder, see Fig. 3. The surfaces of revolution formed by these two lines and the two cylinders may be taken as bounding surfaces of the enclosed region, which will be assumed to have within it a potential

$$V_1 = B \log_e r + A$$

where r is the distance of the point, whose potential is V_1 from the axis of the cylinders and B and A are constants determined from the potentials of the two cylinders. The equipotential surfaces of the field will intersect the surfaces of revolution formed by the two lines in circles, the planes of which will be perpendicular to the axis of the cylinder. If each circle were a conductor connected to an outside source having the same potential as that of the equipotential surface on which the circle lies, the distri-

bution over the surface so produced would cause the potential within the enclosed region to be equal to

$$V_1 = B \log_e r + A$$

If, instead of the external cylinder, a disk be substituted of infinite radius with a hole in it of the same diameter as the cylinder, and with its plane at right angles to the axis of the cylinders, and if the internal cylinder be provided with a similar

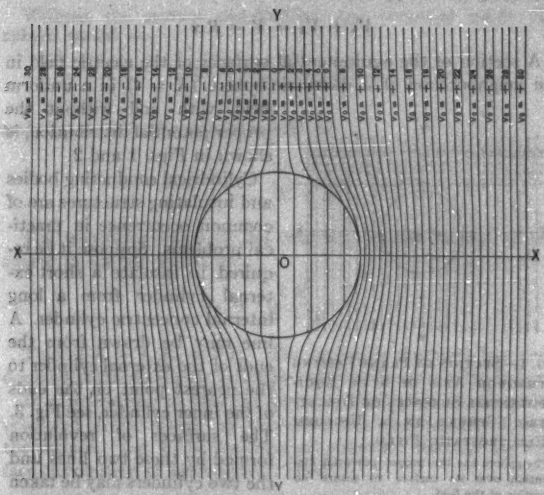


FIG. 2—DIELECTRIC SPHERE (K = 4) IN UNIFORM ELECTROSTATIC FIELD

Section by plane passing through axis of X of equipotential surfaces in neighborhood of sphere. The value of the potential of each surface is given in the figure.

disk at each end; taking z as measured from the point of intersection of the axis of the cylinder and the plane of the middle disk, a field may be assumed between the middle and upper disks, having its equipotential surfaces parallel to the disk, and the potential of the field will be

$$V_0 = C + D z$$

C and D being determined by the potentials of the middle and outer disks.

The region between the inner cylinder and middle disk may be assumed to have an electrostatic field, the equipotential surfaces of which are cylinders concentric with the inner cylinder, and whose values are given by

$$V_1 = B \log_e r + A$$

The surface of separation between the two regions having potentials V_1 and V_0 will have for its equation,

$$r = e^{\frac{C-A}{B} + Dz}$$

$$= a\left(\frac{b}{a}\right)^{\frac{2z}{l}}$$

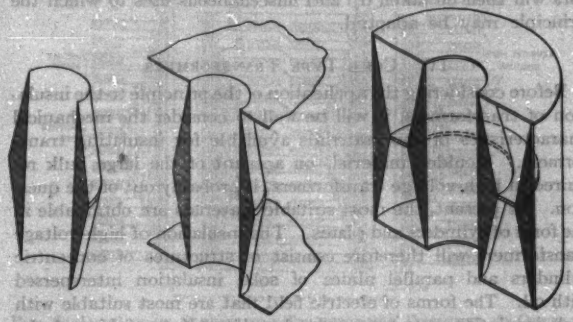


FIG. 3 FIG. 4 FIG. 5

where

$a = e^{\frac{C-A}{B}}$ = radius of hole in outer disk

b = radius of inner cylinder.

l = length of inner cylinder.

If the three disks are limited in diameter, the middle one being less than the other two, and if the region between the two outer disks is completely enclosed by an external cylinder extending from one to the other, the outer edge of the middle disk may be insulated from the external cylinder in a similar manner. These three examples are illustrated in Figs. 3, 4 and 5 respectively.

III. Practical Applications—Limitations

In practical applications of this principle, the means for producing a potential distribution over a surface are limited. A finite number of steps must be used and the potentials must be applied to strips of metal of finite widths in such a way that the intervening surface between two adjacent strips shall have the proper potential at each point. However, with proper care in laying out the various parts, a fairly close approximation may be made to ideal conditions.

The practical application of the principle that at once suggests itself as being most suitable, is the insulation of high-voltage transformers. Accordingly, the problem of insulating high-voltage transformers, particularly such as are used for testing purposes, will first of all be considered. Application to line insulators will then be taken up and miscellaneous uses to which the principle may be adapted.

IV. Core Type Transformers

Before considering the application of the principle to the insulation of transformers, it will be well to consider the mechanical characteristics of the materials available for insulating transformers. Moulded material, on account of the large bulk required in high-voltage transformers, is probably out of the question. At present, the most suitable materials are obtainable in the form of cylinders and plates. The insulation of high-voltage transformers will therefore consist of structures of concentric cylinders and parallel plates of solid insulation interspersed with oil. The forms of electric field that are most suitable with such insulation structures, namely, the uniform field and the field of logarithmic potential, give also the best conditions of stress in the materials and are adapted to the natural form of the winding and core structure of transformers.

The simplest form of high-voltage transformer has one terminal connected to ground through the core and case and the other is brought out through a high potential bushing in the cover. Fig. 6 shows the diagram of connections for such a transformer designed in accordance with this principle. The high-tension winding of this transformer is made up of a number of discoidal-shaped coils, arranged and connected so that the potentials of the coils progressively decrease from the center coils outward. Thus, the coil marked, "terminal coil" has the highest potential, while that marked "ground coil" has the lowest potential.

Each coil is so placed that it lies on the equipotential surface, corresponding to its potential, of an assumed uniform field in the region included between the middle high-potential coils and the outer or low potential coils. The whole high tension winding thus assists in producing in the external region in close proximity to the windings, and in the part of the internal regions which are unoccupied by the cylindrical barriers, what substantially amounts to a uniform electric field.

The external surface of the cylindrical insulating structure which serves to insulate the core and low-tension winding from the high-tension winding is shaped according to the internal field of logarithmic potential and the external uniform field, as

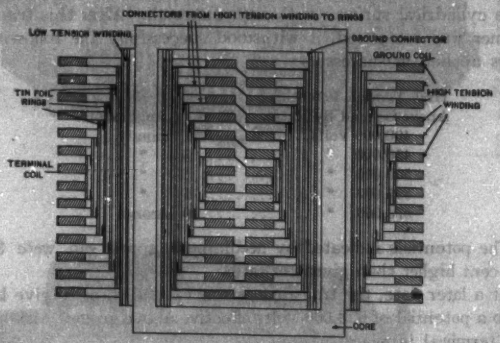


FIG. 6—INSULATION SCHEME FOR TRANSFORMER DESIGNED TO OPERATE WITH ONE END GROUNDED

shown in the foregoing illustrations given in Section II. See Figs. 4 and 5. The potential distribution over the surface of this cylindrical structure is produced by connecting unclosed rings of tin foil on the insulating cylinders to the proper point of the high-tension winding. The top and bottom rings on each cylinder are connected together by a thin strip of copper, which also serves to connect an upper to a lower coil. Thus the ring and its connecting strip lie on the proper equipotential surface of the system, and therefore produce no disturbance in the electric field. Moreover, the ring on account of its width, helps to produce the proper potential at each point of the surface of the cylindrical barrier lying between it and the adjacent ring.

The outlet bushing also is designed so that when in position the end of each conducting layer will lie on the equipotential surface of the system having the same potential, thereby producing the minimum disturbance. This outlet bushing is not shown in Fig. 6.

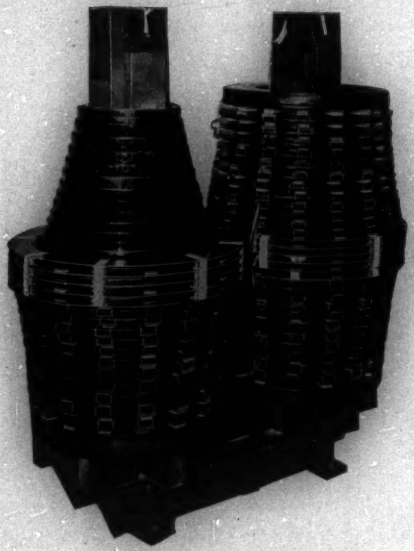
Fig. 7 shows a transformer built according to this scheme partly assembled. Fig. 8 shows the same transformer with coils and iron assembled, but without external barrier. Fig. 9 shows the transformer with external barrier partially assembled, and Fig. 10 shows the transformer complete in tank. No attempt was made to produce an artificial distribution of potential over the surface of the external barrier of this transformer which was made of fullerboard, on account of the impossibility of obtaining true cylindrical surfaces with such material. After this transformer was completed, it withstood successfully the following tests applied in succession:

High Tension Potential Above Ground By Ratio.	Time of Application.
400,000 volts	1 minute.
450,000 "	½ "
500,000 "	1 "
525,000 "	1 "
573,000 "	10 seconds

The potentials indicated by needle point spark gap were 35 per cent higher than given by ratio.

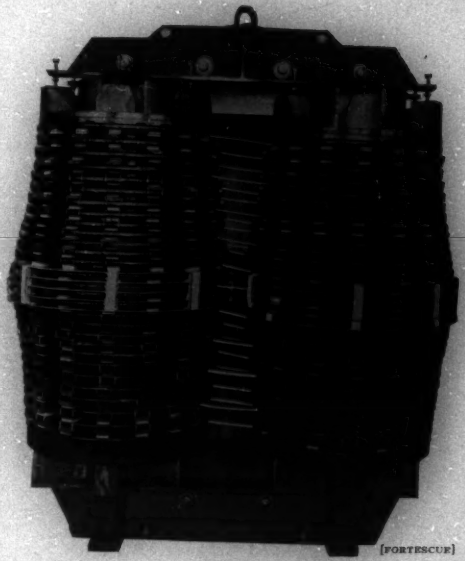
At a later date, the transformer was excited so as to give by ratio a potential of 623,000 volts effective above ground without the terminal in place.

The form of transformer next in degree of simplicity is designed to operate with the middle point of its high-tension winding grounded. Instead of one transformer designed to operate in this manner being used, two transformers, like that already described, may be used, and while it is somewhat more costly to make two such transformers, there are advantages in having two units that can be used for testing independently. When two transformers are used in this way, the difference of potential obtainable with the same conditions of insulation stress is double that of one. Thus two transformers, each capable of producing 500,000 volts to ground when so combined, will be equivalent to a one million-volt transformer with the middle point grounded. The design of a transformer to operate with the middle point grounded may be made according to the scheme shown in Fig. 11.



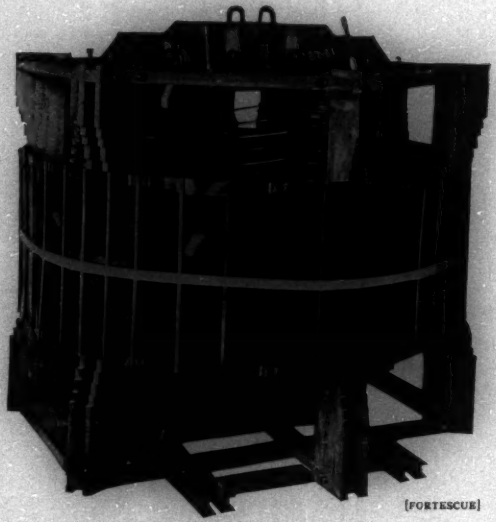
[FORTESCUE]

FIG. 7—TRANSFORMER PARTLY ASSEMBLED



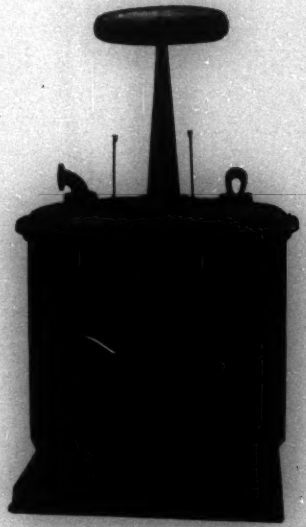
[FORTESCUE]

FIG. 8—TRANSFORMER WITH EXTERNAL BARRIER REMOVED



[FORTESCUE]

FIG. 9—TRANSFORMER WITH EXTERNAL BARRIERS PARTIALLY ASSEMBLED



[FORTESCUE]

FIG. 10—TRANSFORMER COMPLETE IN TANK

A transformer is sometimes required capable of operating with either end of the high tension winding grounded. A design for such a transformer may be made according to the scheme shown in Fig. 12. The insulating structure between the groups of coils on different legs may be made up of flat sheets, in which case the surface potential may be such as to give a uniform field. Instead of a structure of flat sheets, a cylindrical structure, completely surrounding the groups of coils on each leg, may be used, in which case, the proper potential distribution is such as will produce in the structure, a field of logarithmic potential. Besides acting as insulation between the two groups of coils, the cylindrical structure forms part of the insulation to ground, but it is

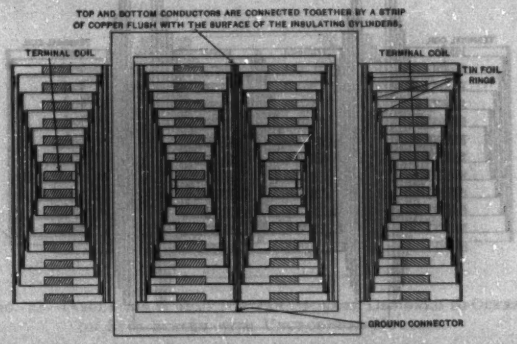


FIG. 11—INSULATION SCHEME AND COIL ARRANGEMENT FOR TRANSFORMER DESIGNED TO OPERATE WITH MIDDLE POINT GROUNDED

hardly practicable on account of the high cost of insulating cylinders of very large diameter.

V. CORE TYPE TRANSFORMERS FOR POLYPHASE CIRCUITS

Conditions of operation on polyphase circuits are somewhat different from those on single phase circuits. A brief description will be given of the changes required to adapt the schemes for insulating transformers shown in the last section to polyphase circuits.

For grounded three-phase star systems, the scheme shown in Fig. 6 may be used unchanged. For ungrounded star systems

this design may be modified by the addition of extra insulation between core and windings to protect against stresses due to one wire becoming grounded. The insulation included in the coil grouping, in this case, should be considered as a separate region, because external bodies may have their potentials changed relatively to the winding. Accordingly, the potentials of the windings themselves will also be raised or lowered relatively to external bodies. Therefore, to maintain the electric fields in the coil grouping and included insulating structures unchanged, it is necessary to consider all this space as a separate region. The

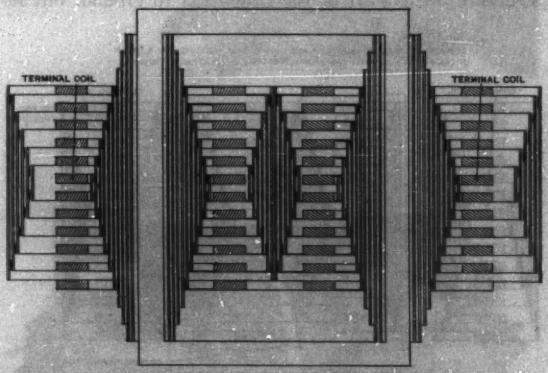


FIG. 12—INSULATION SCHEME FOR TRANSFORMER DESIGNED TO OPERATE WITH EITHER END GROUNDED

intensity at each point within this region will then be independent of the potential of the coils relative to ground. For the region external to the winding included between the cylinder and coils of lowest potential of the winding system and the core, the proper potential distribution over the surface may be obtained by means of a system of concentric cylindrical condensers of equal capacity, varying in length by equal steps, according to the principle used in the condenser-type terminal. Fig. 13 shows a scheme of insulation for such a transformer.

For delta connection, transformers may be a modification of design shown in Fig. 12, additional strength between windings

and core being secured to take care of stresses when one winding becomes grounded.

Figs. 14 and 15 show polyphase transformers designed according to the principle.

VI. Shell Type Transformers

Figs. 16 and 17 show the arrangement and connections of the high and low-tension coils of a shell-type transformer designed to operate with one end permanently grounded. Here the coils themselves correspond to the equipotential surfaces of one region, their potentials decreasing progressively from No. 1 to No. 9. In the regions included between the coils and iron, the surface

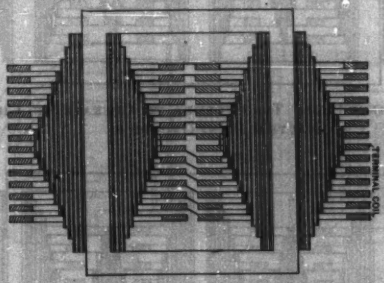


Fig. 13—Insulation Scheme for Transformer Designed to Operate on Star System with Ungrounded Neutral

potential is determined by the coils themselves, so as to produce approximately a uniform field. Fig. 16 shows a section through the middle of the group at right angles to the plane of the core laminations, while Fig. 17 shows a section of one side of the coils parallel to the plane of the laminations. A single group only has been shown. If more groups are used, each group may be wound in the same way, and insulated from the adjacent low-tension winding and iron, according to the potential of the outer coils.

A shell-type transformer, designed to operate with its middle point grounded, may be made up of two groups connected as shown in Fig. 18, the inner coils of each group being the high-potential coils, and the outer being connected to the iron and case and grounded.

For polyphase systems, modifications of the designs shown above may be used. These modifications are of the same nature as those required to adapt core type single-phase design to designs for operation on polyphase circuits, and need not be gone into any further.

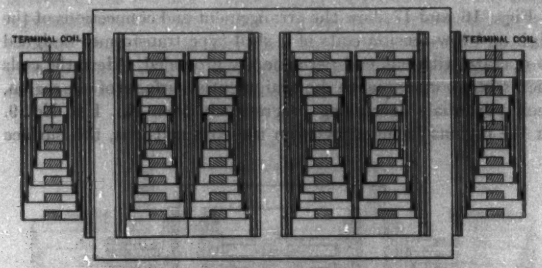


Fig. 14—Three-Phase Transformer to Operate on Circuit with Neutral Point Grounded

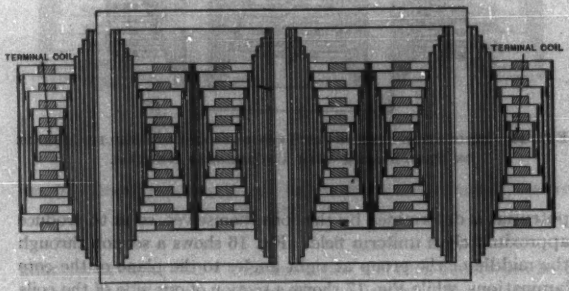


Fig. 15—Three-Phase Transformer Designed to Operate on Ungrounded System

VII. Application of the Principle to the Design of Outlet Terminals and Insulators

In core-type transformers, designed according to the principle, the outlet terminal forms part of the insulation system of the transformer, and must be designed in accordance with the same principle. One way of doing this would be to produce within the

body of the terminal a logarithmic potential by means of rings of tin foil connected to the proper points of the transformer winding. This method, however, is not convenient. A better plan is to obtain the required surface potential distribution by means of a system of concentric condensers.

The condenser type terminal, as it is commonly called, affords a conspicuous example of the successful application of the principle stated in Section II of this paper. As commercially made, this terminal consists of a series system of concentric cylindrical condensers of equal capacity, so arranged that the ends of the conducting cylinders form, at the outer surfaces of the terminal, a potential distribution corresponding to that of a uniform field, the equipotential

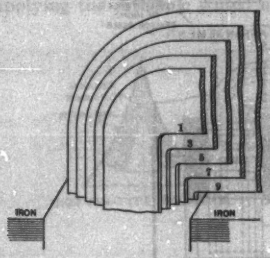


FIG. 16

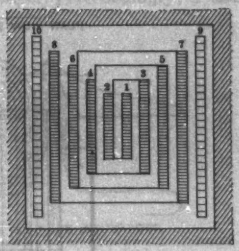


FIG. 17

surfaces of which are at right angles to the axis of these cylinders. To conform therefore to the principle stated in Section II of this paper, the space external to the terminal must be bounded by two infinite parallel conducting planes perpendicular to the axis, one at the tip and the other at the end of the conducting cylinder of largest diameter, and connected to the conducting cylinders at these points. In practise, this condition is approximated by placing a disk-shaped conducting body at the end of the middle cylinder, and making the surface of the cover through which the terminal passes as free from projections and ridges as possible.

A comparative test has been made on a terminal of this type, first with a small disk, and then with a large one, which illustrates in a remarkable way the importance of the proper application of the principle. The terminal when tested with a small

disk, at a potential above ground of 300,000 volts, showed signs of corona, which extended to the rings at the edges of the tin foil cylinders at 350,000 volts. At 400,000 volts, the whole terminal was lit up with corona. It was not found advisable to raise the vo tage above 420,000 volts for fear of rupturing the terminal. The small disk was then replaced by a large one five ft. (1.52 m.) in diameter and one ft. (0.304 m.) thick with semi-circular edges. With this disk the terminal showed no signs of corona up to 573,000

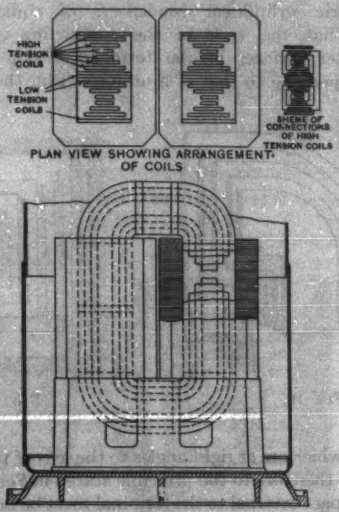


FIG. 18—SHELL-TYPE TRANSFORMER DESIGNED TO OPERATE WITH MIDDLE POINT GROUNDED

volts. These potentials are those obtained by ratio. By a needle spark gap, the values indicated were 35 per cent higher.

There are other ways of constructing a terminal, depending upon the same principle. For example, instead of using a system of concentric cylindrical condensers, a system of parallel disk condensers of equal capacity might be used, the diameter of the disks being such that the distribution of potential over the surface of the internal region of the terminal will correspond to a

logarithmic potential, with proper relations between the inside conducting cylinder and the inside edge of the outer disk. The intensity within the terminal may be limited to any assigned value. A terminal designed in this manner would occupy more space than the condenser type terminal, but might have advantages where it is desirable to make the overall length as short as possible.

A transmission line insulator consists of a system of condensers in series. To obtain an equal division of potential difference between insulators, is not the only requirement of a successful design. This condition may actually be obtained, and yet the system of insulators will break down at a very much lower potential difference than the sum of the breakdown strengths of each insulator. The strength of the system may be increased by applying the principle stated in this paper. Accordingly, if the

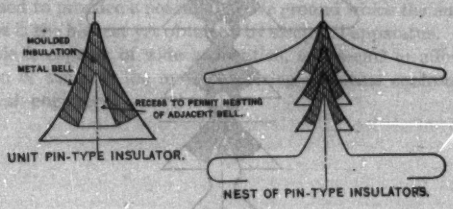


FIG. 19

units of which the insulator is composed are equally spaced, and have each the same capacity, the high- and low-potential conducting surfaces which are insulated from each other by the insulator should be so designed as to give as nearly as practicable a uniform field corresponding to the potential distribution at the outer surface of the insulator. For example, Fig. 19 illustrates an element of an insulator, which consists of a metal bell, so designed that it may be used as the electrode of the adjacent insulator. A dielectric compound is moulded into the above mentioned bell, so that it will have a recess for the adjacent bell to nest into. The surface of the dielectric, which is intercepted between two adjacent bells, is moulded so as to conform to the lines of force of the electric field between the two adjacent bells. A nest of these may be used as a high-voltage insulator, and each insulator will take up approximately an equal share of the differ-

ence of potential, but in order to obtain the highest efficiency from the insulator, an arrangement of parallel discoidal-shaped electrodes, like those shown in Fig. 19, must be used. The external field will then be substantially uniform, and agree with the division of potential between the individual insulators. The efficiency of the combination is thereby increased in exactly the same way that the efficiency of a condenser type terminal as an insulator was increased by the addition of the large disk, namely, because it completed the surface distribution of the region surrounding the terminal in accordance with the principle.

A unit insulator, made according to the above plan, conforms to the law of similar fields. Thus, if the dimensions are doubled,

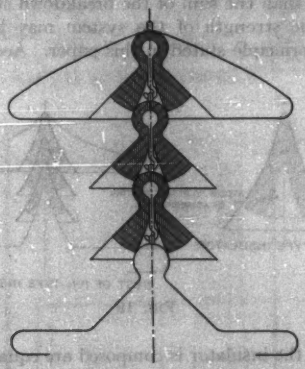


FIG. 20

the breakdown voltage is doubled. The cost of an insulator of this kind will vary approximately as the cube of the voltage. If, by some such method as that outlined in the last paragraph, the efficiency of a nest of insulators can be made to equal that of each individual unit, and if this can be done at a reasonable cost, then the cost of an insulator of this type will vary directly with the voltage for which it is designed. It is therefore obvious that an insulator, consisting of a nest of small insulators, would cost less than a large single insulator designed for the same voltage.

The principle may be applied to suspension type insulators, also, as shown in Fig. 20. Other types of insulators besides those shown may also be assisted by the application of this principle,

but the advantage to be gained is not so evident as in the type shown.

VIII. Miscellaneous Applications

The well known principle of the guard ring is a particular case of the principle stated in Section II, and so also is the method of protecting instruments by means of grounded metallic coverings. The principle gives the method by which a given electric field may be maintained constant within an enclosed region, independent of the influence of external bodies. It may therefore be used to protect systems of charged bodies from the influence of other bodies. There seem to be many possible applications of the principle in high-voltage investigations.

IX. Conclusions

The principle stated in Section II of this paper has been used to insulate a high-voltage transformer. This transformer has been used to produce a potential above ground which the author believes is the highest yet obtained by electrical apparatus. The principle is capable of wide application, and seems to afford a solution of some of the most perplexing problems confronting electrical engineers.

DISCUSSION ON "AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY" (FORTESCUE AND FARNSWORTH) AND "THE APPLICATION OF A THEOREM OF ELECTROSTATICS TO INSULATION PROBLEMS" (FORTESCUE), NEW YORK, MARCH 14, 1913.

Percy H. Thomas: There are two principal conclusions or principles in these papers which we should carefully distinguish. First, where solid dielectrics are combined with air in the insulation of terminals of any kind, advantage is gained if the solid insulator is shaped in a particular way; that is, if the outline of the solid material follows what may be called a line of electrostatic force extending from the positive to the negative terminal. Second is the intelligent control of the static potential at all points between the two terminals. This principle is illustrated by the so-called "condenser" transformer terminal. Instead of applying 100,000 volts between two terminals and allowing the potential to take its own natural distribution, Mr. Fortescue inserts a number of conductors at various points between the terminals, and then impresses on each particular intermediate conductor the potential he thinks it ought to have. The net result is a gain of three or four hundred per cent in the voltage which can be withstood by the same length of air gap. The advantage comes about in this way—we get a relatively high voltage resisted by a definite air gap, when the fall of potential is distributed equally through the whole length of the air gap. By devising some scheme which will make every portion of the air gap work to its maximum limit, we succeed in getting the greatest effectiveness that is possible out of the available separation.

The one critical thing which determines this distribution of potential along the air gap, in other words, which determines the electrostatic intensity of the electrical field through the gap, is the shape of the terminals. The electrical field has a uniform intensity along a line of force only where it is between terminals in the form of wide parallel planes. Wherever the terminal exposes an edge, or form of that sort, there will be a concentration of the lines of force, that is, a high intensity where these lines concentrate and a low intensity somewhere else. In this case the only part of the air gap that does its full duty is that at the point of greatest concentration. From this it can be seen why it is desirable to establish the potential at a number of intermediate points between two terminals separated by insulating material. Suppose we have two terminals a foot in diameter, separated by a distance of two feet. Evidently the field between will not be uniform, since these plates are relatively small in dimensions in proportion to the distance between them. If, however, we place two similar plates one inch apart, the stress between them will be substantially uniform at all points. Therefore, if we interpose between the two terminals separated by the

space of two feet, a number of similar plates, each spaced an inch from its neighbor, and if we at the same time impress upon each intermediate plate a potential a little higher than the potential of the previous plate, so that the total potential is divided evenly between them, then will all the space between the original plates be stressed uniformly, and the maximum insulation strength possible will be obtained.

I would like to call attention to one point, since we have recently been discussing the relative effect upon insulation of stresses at ordinary frequencies and at high frequencies. The principles and methods set forth by the authors do not involve the frequency directly; that is, the ideal arrangement for one frequency will be the ideal arrangement for another frequency, at least so far as the theoretical principle involved is concerned. Considering, for a moment, the first principle as above defined, of using such a shape of solid dielectric as will give an outline which will follow the direction of the lines of electrostatic force, we must recognize two disturbing influences.

The first is the effect of external fields. If we design an insulator of this type on the theory that the line of electrostatic force will no longer be the one which we assumed, the surface chosen will no longer be a correct surface for giving the maximum efficiency. This is a matter which, in some applications of this principle, will be extremely important. Mr. Fortescue has given one excellent example in the condenser type terminal. The necessity of having a large plane on top of the terminal for the best effect, rests in its effect in eliminating the disturbance of the stress due to external fields.

The second disturbing point is the matter of current leakage over the surface. We have a chance for surface leakage of current from one terminal to the other. The resistance value of the leakage path taken by this current may vary from that representing the electrostatic distribution of potential. As a result, the fall of potential along the surface will not necessarily be the same as that produced by the electrostatic field. In this case, the result will be that a charge will accumulate on the surface of the insulation which will change the distribution of the static field to bring it into relation with the drop in potential of the leakage current; that is to say, it would not be safe to plan the insulation from a consideration merely of the electrostatic field, where a considerable surface leakage may be expected.

Since our electrical knowledge has grown up from two or three different and independent beginnings, for instance, from the electrostatic point of view and the electromagnetic point of view, there are usually two ways of looking at the same phenomenon. Mr. Fortescue has considered one method of looking at these electrostatic insulation problems, and a good many have used another method of looking at exactly the same thing, these two methods being, perhaps, mathematically equivalent. For the particular class of problems Mr. Fortescue discussed, his

method is best. For some other applications the other method may be the best. Take the magnetic circuit: we used to look upon it as determined by the magnetic charges located on the surface of the magnetic material, or, in other words, as determined by the resultant effect of the free magnetism appearing at the various surfaces where magnetic flux enters iron or other material of high permeability. Later, however, we began to look at the magnetic circuit as analogous to the electric circuit, and to apply a law analogous to Ohm's law, namely, the law that the magnetic flux in a magnetic circuit is the magnetomotive force divided by the reluctance.

Suppose we have a rod and insulate it from the conductor at any potential, as in a bushing. We know that the metal *a* (Fig. 1) and the rod *b* are at a difference of potential, separated by the insulation *C*. This has long been known as an unsuitable form for resisting high-frequency voltage. One way of explaining this fact is to assume that the point *A* in the sketch represents a small condenser, one plate being the conductor inside the insulating tube and the other plate being the outer surface of the tube. It is well known that any condenser cannot have any potential

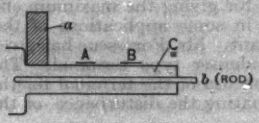


FIG. 1

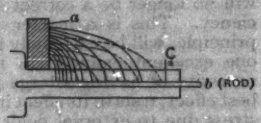


FIG. 2

impressed upon it until a charge is added to the condenser. The surface of the insulation at this point *A* will be the potential of the inner rod, until some charge appears on its surface, that is, until the full potential to be insulated has been impressed between the point *A* and the plate *a*. If, now, this potential is sufficient to break down the air to the point *A*, this point becomes charged to the full normal potential on the terminal and the voltage of *a* is brought to the point *A*. It is, therefore, impressed upon the remaining portion of the insulation *C*, and we may assume a similar jump to a second point, *B*, nearer the end, which will bring the potential of the plate *a* to the point *B*, and so on until a discharge is produced over the whole distance. This has been one customary way of explaining the known inherent weakness of this form of insulation.

In Mr. Fortescue's explanation you have it somewhat as follows: If there were no insulating bushing, the lines of force would be distributed as shown in dotted outline in Fig. 2. If the insulation is now introduced, the resistance of this material to the electrostatic lines of force becomes less, and the lines of force become crowded and more numerous near the plate *a*. This

means a greater intensity of field at the point A as is shown by the lines of force represented by full lines, which, in the case previously assumed, starts the breakdown of the air at this point and a fresh concentrated distribution of the field of force will occur, leading to a total breakdown. These two explanations are different ways of expressing the same mathematical and physical situation and illustrate what I started to say, namely, that some of the phenomenon explained by Mr. Fortescue with great clearness have been previously understood and explained from a different point of view.

The idea of greatest interest, perhaps, and the one which will help us the most, is the second of Mr. Fortescue's principles, that of establishing arbitrarily the fall of potential through the insulation in the manner that we wish to use.

I wish to ask Mr. Fortescue if he will answer one or two questions in regard to Fig. 7, in the paper by the joint authors, as illustrating the effect on the distribution of the field of having a little ring R added to the solid dielectric between the two plates M and N. This produces a concentration of field and increases the intensity at certain points. I would like to ask him whether, as a net result, the total breakdown strength is less than it would be without that little ring. It is conceivable that locally the stress on the air might be greater, as it undoubtedly is, and yet, in view of the added distance that the spark must pass, that the net result would be an increase in the total resistance of the apparatus.

That leads to another question: If we have a distribution of surface of a solid dielectric between two terminals, which produces an excessive concentration of field at one point, does the local breakdown, in fact, have any more effect than removing so much of the total gap? That is, has a breakdown at one point a positive deteriorating effect upon other parts of the gap?

Another caution is needed. If we succeed in determining the form of our field and succeed in getting a form of insulation which will give us the very maximum possible strength from a given separation of terminals, and there is any disturbance in these ideal conditions, the results will be far more harmful than would have been the case with a less favorable design of the potential distribution. It is generally easier to upset a perfectly ideal condition than one where reliance is placed on thick material and wide spacing.

I infer, from what Mr. Fortescue says, that we must give up the idea of having a positive and a negative terminal in the same high-tension transformer when we go up to perhaps 100,000 volts.

Ralph D. Mershon: These papers are admirable. They are not only valuable and interesting—they are fascinating. I emphasize this, because a little later I shall criticize one of them, and I would not have you think I undervalue the paper, or the beautiful work it presents.

Referring to the joint paper, there are a number of things about

it, aside from the general subject, that appeal to me very strongly. For instance, the scheme of Fig. 3, using a pantograph. I do not know whether that is original with the authors, but whoever devised this scheme has done an effective and ingenious thing. I am surprised and disappointed that they did not get results agreeing more closely with theory than those shown in Fig. 4. Possibly the discrepancies are due to the e.m.f. of decomposition of the salt solution.

On page 899, the question of "creepage" distance is brought up. Mr. Thomas has already referred to it and I hope the authors will bear rather forcibly upon it when they make their closure. It seems to me there is a possibility of the action Mr. Thomas suggests. When in the past a corrugated surface has been used, I think it was not primarily used for the purpose of insulation, in the sense that the authors of the paper have assumed. I think that usually the surfaces would have insulated properly, without grooves, so long as they were clean, and that the grooves were used in order to increase the length of path and, therefore, the resistance of any dirt that might get on to the insulator. The authors speak of the fact that they have tested insulators with dirty surfaces. I have made tests with insulators purposely sprinkled with dust, in the endeavor to simulate the conditions of practise, and have found the results not at all the same as those obtained with insulators that had gathered dirt in their own peculiar way.

Mr. Thomas referred to the matter of frequency, and stated that surfaces made in the way described by the authors would not be affected by frequency. It seems to me there may be some question about that, especially with the very high frequencies ascribed to lightning.

The effects of high frequency have been emphasized in my mind by some experiments I saw not long ago at Leland Stanford University. Prof. Ryan is now doing some work with sustained high-frequency current, using a Poulsen arc and getting voltages up to 35,000 and frequencies as high as 1,000,000. It is startling to see what the high frequencies do and the difference between their effects and those of ordinary frequencies, both as to distribution of voltage over an insulator, and the effect on the insulator itself. For instance, 35,000 volts, at a frequency of 250,000, will in a few seconds go through an inch of porcelain just as you might poke a skewer through a piece of cheese.

I want to second Mr. Thomas's request that the authors give us some idea as to the effect of surrounding objects. For instance, what will be the effect on transformer terminals if the transformer is in a small cell? Is the conductivity of the ordinary masonry wall sufficient to materially change the distribution? Suppose some time we wanted to install a transformer within a cell made of something that is a better conductor than masonry—what precautions must we take in the case of terminals built in this way?

Now, turning to the paper of Mr. Fortescue—as I said before, it presents a very beautiful piece of work. But it is a pity, I think, that a piece of work as valuable as this is not more clearly presented. It seems to me that this paper ought to be worked over very carefully, and so modified as to make it more readily intelligible to those who may have occasion to refer to it in the future. I sincerely hope that Mr. Fortescue will endeavor to work it over in that way.

The trouble with investigators and engineers is that they are usually so saturated with their subject that they cannot realize the fact that the man to whom they are trying to impart information is not similarly saturated. They have gradually come to the point of saturation themselves, and having arrived there are so thoroughly permeated with the subject that they cannot realize the fact that they got their information by slow processes. In explaining they omit many of the mental steps by which they arrived and which should be included, so that those who read what they produce may clearly understand. It is not enough to write engineering and scientific papers so that they can be understood; they should be so written that there can be no possibility of their being misunderstood. To my mind, the best example we have of that sort of writing is the works of Silvanus P. Thompson. I think he is a past master of instructional writing. I have never read anything of his that did not conform to the criterion just laid down, and I think we can all take him as an example.

It is not quite clear to me whether the treatment of the insulator at the end of Mr. Fortescue's paper is an overlapping of the treatment in the joint paper, or not, and I would be glad if Mr. Fortescue would make this a little clearer.

Comparing the two papers, the one that appeals to me most is the joint paper. Although the results outlined in Mr. Fortescue's paper are undoubtedly of very great value, and exceedingly interesting, the method of accomplishment, is, so to speak, more brutal than that of the other. The method of Mr. Fortescue's paper is like nailing a thing down with a railroad spike, whereas that of the other is like tying it up with a silk thread. I think that is the reason why this joint paper is so much more fascinating to me than the other, although the results of the other paper are, no doubt, just as valuable, perhaps in some ways more so.

C. O. Mailloux: I may not be able to contribute very usefully to the discussion of these papers, having seen them for the first time only as I came in the meeting. Nevertheless, I feel prompted to say something in justice to the authors, because the impressions produced upon my mind by these papers are quite different from those seemingly produced upon the preceding speaker. As I listened to the presentation of the abstracts of these papers, my interest in and admiration for them grew rapidly; and I thought it only right to let the authors know it.

I have a high opinion of these papers. I think the Electro-

physics Committee is to be congratulated upon having presented them. I regard them as possessing the highest interest, both theoretically and practically. Indeed, I am tempted to characterize them as being, in a sense, epoch-making. It seems to me that they afford another interesting example of the fact that great practical results may be reached through highly theoretical and even somewhat abtruse considerations.

We have all had occasion to realize that pure theory may, and occasionally does, prove a clear-sighted prophet and a most helpful guide by whose assistance results of the highest practical value are attained in a relatively simple manner, sometimes after all previous efforts to secure them by means more direct and adequate have failed completely. The paper of Mr. Fortescue seems to me to be one of that rare and valuable kind. As I listened to the abstract, I remembered that five years ago, in a discussion of engineering education, before this Institute, I called attention to the importance and desirability of an engineer being trained so as to be able, on occasion, to attack and to solve problems by entirely theoretical methods. I cited, as examples, two cases where a triumph in electrical science and engineering was achieved as the result of the solution of a differential equation. It is worth while to recall them here as edifying deeds. The first of these triumphs was achieved more than fifty years ago by Kelvin, who, by finding " particular solutions " of a differential equation, which has since become known to us as the " telegraphers' equation," rendered submarine telegraphy possible, and in fact was able to foresee, forecast and specify all the essential facts, features and difficulties involved in submarine telegraphy. The second triumph was achieved a half-century later by Dr. M. I. Pupin, who, by finding the general solution of the same equation, made clear for the first time new physical features and characteristics, and modernized long-distance telephony, by rendering very easy that which had seemingly been impossible before. In connection with this very subject, I might add that the excellent work of Dr. Kennelly in the study of the characteristics of long transmission circuits—constituting interesting extensions and applications of the same theoretical principles—furnishes another example of the way in which theory may blaze out a path which proves to be the shortest cut to the best practical methods.

Mr. Fortescue's paper has, in my opinion, the rare merit of being at the same time intensely theoretical and intensely practical. In this paper, theoretical considerations are used very intelligently to assemble and co-ordinate certain facts, to develop conclusions from them, and to point out the way to very interesting and far-reaching practical applications.

The preceding speaker finds the paper lacking in clearness. The abstract of the paper given by the author seemed to me to be lucid enough, especially after reading and noting the statement of principle of electrostatic theory, given in the paper. It so happens that the principle here referred to could be presented and

made clear in many different ways; and this paper is of a kind whose clearness may depend as much on the habits of mind and thought of the person who reads it, as of the one who wrote it. I say this in all seriousness, and without wishing in the least to disparage the type of mind or the habits of thought or study of any person whatever. Some persons, it is known, can see theoretical principles very clearly from a geometrical or pictorial point of view; others see them best from a mathematical or analytical point of view; still others see them best, or perhaps only, through a physical description; and, lastly, there are those who can see them from all points of view. Personally, I think it would have been a good idea to have put in an appendix to this paper, a resume of the mathematical theory referred to on page 909. Had this been done, those of you who have studied the Theory of the Potential Function would doubtless have recognized some other old acquaintances besides "Green's theorem". The sight of an equation may suffice, often, to put one on speaking terms again with an idea or a principle that one already knew either analytically or geometrically or physically, or in all three ways. In the case under discussion the ideas and principles are much better known than might be supposed at first. They are as simple as they are beautiful. The author should be congratulated for having placed before us something which has been in our reach for a long time, and which, though as simple as the egg-trick of Columbus, yet has been unnoticed and passed by, by most of us. It is not at all difficult to understand the theory which is involved. You are all really quite familiar with it already, I am sure. We have had to do, in this case, with equipotential *surfaces*, which in a space of three dimensions become equipotential *envelopes*. A toy balloon of thin rubber, inflated with gas, gives an ocular demonstration of a "surface" constituting an "envelope" which may be, in a sense, called "equipotential". In that case we have, on both sides of the envelope or shell, an equilibrium of *pneumatic* "pressures," whereas, in the case of an equipotential electric envelope, we have equilibrium of electric "pressures" or potentials on the two sides of the envelope. In electrophysics, we have equipotential "envelopes" or "shells" of two principal kinds, namely one in which the potentials are electrical forces or pressures, which are familiar to us by the indications or effects which they can produce on a voltmeter, and also another kind in which the forces are magnetic. In both cases, the surface passing through all points of the same potential is an equipotential surface, and this equipotential surface becomes an equipotential envelope in the case of an isolated electrified or magnetized body. The iron sphere used by Lord Kelvin as the "envelope" of his "ship-galvanometer" to make it independent of the magnetization of the earth or of the ship was, in a sense, an equipotential magnetic shell. It also answered the purpose of a "barrier", to borrow a term from the theory of the potential function. Mr. Fortescue has done something analogous. Starting from and

guided by considerations which usually would interest only the mathematical physicist, he has evolved from intensely theoretical ideas an intensely practical conclusion and method. I think that the analogy of the toy balloon which I have just referred to will enable us to get a pretty good idea of what he has sought to do theoretically and what he has accomplished practically. Let us suppose that while the little balloon is being inflated, it shows a tendency to bulge and to form excrescences at one or more places. It would still be an equipotential surface, but there might be more strain on the thinner and weaker parts which are bulged out excessively. If now we find some way of applying a counter-potential or a balancing potential, it will reduce the bulge and make the balloon as a whole spherical once more. We would thereby reduce the excessive strain produced at the weaker points. This would be accomplished, for instance, if the toy balloon were enclosed in a hollow metal sphere or spherical shell, because the bulging parts coming in contact with the inner surface of the shell, would be prevented from further bulging and straining. In analogous manner, Mr. Fortescue seeks to apply balancing or compensating potentials to different points of an electromagnetic winding, so as to keep the equipotential envelope from bulging too much or to keep it within bounds, so to speak. This is undoubtedly a very interesting and captivating feature of his paper. I consider it a theoretical treat as well as a practical feat.

F. W. Peek, Jr: These papers bring out in a very interesting way the dielectric circuit. How in design we must not think of voltage and insulation thickness alone, but of dielectric flux.

When energy was first transmitted electrically low voltages and large currents were used. Therefore, it was not necessary to bother much with a study of insulation, but the magnetic field was of necessity investigated and studied. We would not think of building apparatus in which the magnetic circuit was badly out of balance or in which the lines were very much crowded in one place. Yet balance of the dielectric circuit is of much greater importance than balance of the magnetic circuit.

In these days of high-voltage engineering the dielectric circuit must be considered in the same way the magnetic circuit is considered—and not as "charges" or as something connected with rubbing glass rods on silk, pith balls, etc., as, unfortunately, it is still taught in some of our colleges. Naturally in all intelligent high-voltage designs the dielectric circuit is considered.

The dielectric circuits and magnetic circuits are in many ways analogous. Thus to establish the magnetic field there is the magnetomotive force, to establish the dielectric field the electromotive force; corresponding to the magnetizing force or magnetomotive force per centimeter of circuit there is the electrifying force or gradient or volts per centimeter of dielectric circuit; magnetic flux density; dielectric flux density, etc. Insulation ruptures when the dielectric flux density exceeds a given value, or the force producing the flux exceeds a given value. The flux density at

a given point is proportional to the gradient at that point, that is, $\frac{de}{dx}$. The gradient may thus be considered as a force or stress on the insulation, and the flux density the resulting electrical strain or displacement. This is analogous to Hooke's law of mechanically elastic bodies. When the force or gradient exceeds the elastic limit, rupture occurs. The permittivity or specific capacity of a dielectric is a measure of its "electrical elasticity". The permittivity for air is (1) and for glass (5). Thus with the same gradient or electrical force the displacement or flux density is five times in glass what it is in air. But it takes about twice the force or gradient to rupture glass, therefor at rupture glass is displaced ten times as much as air. Thus air is electrically stiff and glass is electrically elastic. In most forms of insulators, leads, etc., air is unfortunately necessarily in combination with a solid dielectric. When glass or some other solid dielectric is placed in series with air the solid, for the same displacement or flux density, requires a lesser gradient or stress; most of the stress is thus put on the weaker air, which ruptures.

Naturally in design, then, it is our general object to so proportion the insulation that the stress or gradient is proportional to its strength; that is, for a given insulation, to make the flux density uniform, and for a combination of insulations, to so arrange them that in the combination the one does not weaken the other but that the stronger actually relieves the weaker, or in other words so that the flux density is greater in the one of greater permittivity and strength. This must apply to the internal strains as well as the so-called leakage strains.

The authors have shown that by making the solid insulation tangential to the lines of force the field is not distorted and the stress on the air is not increased by the introduction of the solid. This is a step in the right direction, but it however does not necessarily give the best form for the solid, for although the addition of the solid does not put extra stress upon the air, it also does not tend to relieve the air at the point of greatest flux density.

For internal strains the arrangement of conductors should be considered and is, as for instance, in a transformer by arrangement of conductors and coils, where extra metal for this purpose is not generally necessary. For instance, if two conductors of a given diameter are taken and placed a given distance apart the insulation may break down at say 85,000 volts; if these conductors are now split up into six conductors an arrangement may be made which will require 100,000 volts to rupture.

It is proper and necessary to consider all such features in design, but as in all engineering work there must be a compromise; apparatus must be designed not only to meet normal conditions, but also to meet abnormal conditions. We have, so far, only considered high voltage at low frequency.

Suppose, now, coils, insulators, etc. are designed so that the stress is everywhere evenly distributed. To do this the insulation must be thinned out at one point and thickened at another point. Now in case of high frequency the whole voltage may be localized at the point where the insulator was decreased in thickness. Hence ideal insulation for normal frequency may in no way be practical but break down immediately with the first surge or lightning stroke. This means that the design must sometimes be modified from the "ideal"—not always or even generally, but it is a point which must always be considered. It can be readily seen how this localization of potential can happen, especially in certain types of apparatus as at the point of thin insulation the potential may pile up due to the reactance and capacity combination at this point. It is of utmost importance in design to consider this and modify the "ideal" design accordingly when necessary, and undoubtedly this has been considered by the authors of these papers.

Then in the design of leads, bushings, etc., the details must often be modified to take care of weather conditions. In transformers in order to get an "ideal" design the connections may be too complicated. In leads or insulators consisting of a large number of metal parts care must be taken that the "multigap effect" does not exist as in the well known lightning arrester of that name.

The condenser lead is ideal in many respects, especially at normal condition; though the practical design is possible, and a fact, it is not as simple as would appear. For instance, if the capacities of the cylinders are made equal, true balance is not approximated, as each cylinder has a different capacity to ground and to the center terminal or tube. These to ground capacities and to lead capacities tend to neutralize each other, but can not always do this and may cause concentration of flux or potential at any point.

Regarding insulators built as in Fig. 20 in the paper on "Insulation", if a single unit gives balance or equal strain the combination of equal units as shown cannot possibly do this, but potential will be greater on some units than on others. To get equal balance not only must the flux be uniform, but the total flux must be the same on each unit. As can be seen for the combination, each unit has a different capacity to ground and to line. This means that the total flux is not the same on all units, and therefore, potential is not equally divided. This does not condemn the design, however, but such a combination may be worked out with different sizes of units as it also can be in the commercial insulator of today. In a design of this sort the high-frequency multigap effect must also be guarded against. That balance can not exist has previously been shown for commercial insulators.*

I wish to say again that these papers are of exceeding interest

Electrical Characteristics of the Suspension Insulator, TRANSACTIONS A.I.E.E., Vol. XXXI 1912, p. 907.

and importance because they bring forcibly before engineers the fact that a consideration of the dielectric circuit has a greater and more practical sphere than that of the pure physicist and mathematician, and that it must be considered as the magnetic circuit has for years been considered by practical engineers.

A. E. Kennelly: The papers before us are not only important from a practical standpoint, but they also indicate defects in our working theory of electrostatics.

We are accustomed to say that air breaks down between parallel plates when the intensity reaches 3000 volts per mm., or 30,000 volts per cm., and we are in the habit of thinking of it in gradient of potential. The reason, perhaps, that we select that method of expression, is that we have a unit that is easily expressed;—*i.e.*,volts, and the inch or centimeter, so that we have a unit easy to apply. But it is equally correct to say that air breaks down when the static flux-density exceeds a certain critical value. That is a very important generalization. The reason we do not put it that way is, perhaps, because we have no name for the unit of electrostatic flux density. We have a unit for the magnetic flux density—the gauss. Personally I call the unit of electric flux density the stat-gauss, which is, of course, objectionable slang, but it has, at least, the merit that it is self-explanatory. It would seem very desirable to name the static unit of flux the "Kelvin", to correspond to the maxwell. It would seem very proper that Lord Kelvin's great name should be attached to the science of electrostatics in which he did such magnificent work. If we assume that the gradient of impressed potential in air, which produces breakdown, is 30,000 volts per cm., we realize that this corresponds exactly to 100 stat-volts per cm., since the static volt is just 300 volts. One hundred stat-volts per cm. would produce in air a flux density of 100 kelvins per sq. cm., that is to say, the critical flux density producing breakdown in air is, by the foregoing reasoning, 100 kelvins per sq. cm.

These papers may be summed up by saying that where you have two insulators associated together, their contour must be so selected that at no place does the electrostatic flux leave the air to go into the other medium of greater specific inductive capacity, because if it does, there is danger of producing an undue flux density, too many kelvins per sq. cm., in the air, tending to overstress it and break it down locally.

Philip Torchio: I am very much interested in these two papers, and I would like to point out that these theorems and their application are not confined only to high voltages, in the order of 100,000 volts, but also apply to very moderate generator voltages of 4000 volts up to 20,000 volts. I want to show several effects that we obtained in making a voltage test on dielectrics in series with air as applied between a cable insulated with 10/32 in. (7.9 mm.) of rubber, one in. (25.4 mm.) of air space and a needle point mounted on a ground plate, this plate

and the conductor being respectively connected to the terminals of the transformer, as in Fig. 3.

When we applied 5400 volts at 25 cycles, Fig. 4, the needle point became luminous with corona. At 13,000 volts, Fig. 5, the braid also became luminous at the point opposite the needle. At

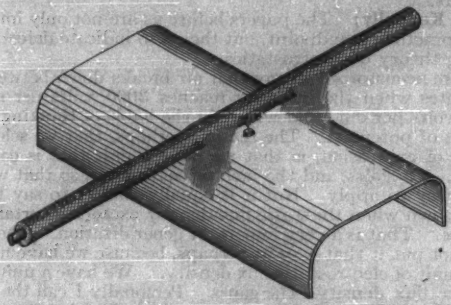


FIG. 3—GENERAL ARRANGEMENT
One inch between cable braid and needle point mounted on ground plate. Transformer connections omitted.

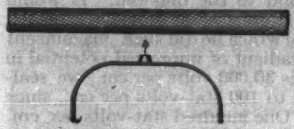


FIG. 4—5400 VOLTS
Corona at needle point.

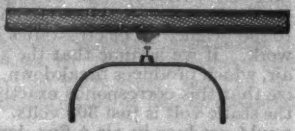


FIG. 5—13,300 VOLTS
(27,700 volts, streamers, needle point to braid.)

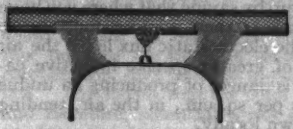


FIG. 6—34,200 VOLTS
Corona, bands from curved surface of braided cable, separate from, and apparently repelled from needle point streamers.

FIG. 7—42,100 VOLTS
Very vigorous streamers from needle point. Occasional discharge streamers through border corona.

27,700 volts the two luminous zones grew together, and discharge streamers took place between the needle point and the braid. At 34,000 volts, Fig. 6, a curious phenomenon occurred; at the borders of the round edges of the plate, at about two in. (50.4 mm.) separation between plate and braid, two separate coronas formed,

having a rounded shape, which seemed to be repelled outward by the field of the streamers at the needle point. At 42,000 volts the streamers between needle points and braid, Fig. 7, were very violent and also occasional streamers took place between border coronas. In this case the cable withstood for about five minutes 42,000 volts under those conditions without failure and then the test was stopped. In other cases we had failures.

I have also an interesting set of photographs, giving a photographic record of this corona effect at very moderate voltages. These photographs will be found accompanying my discussion of Mr. Lamme's paper of last January. The explanations then given, indicate the importance of overcoming the dangers of corona for voltages of only a few thousand volts when air is in series with dielectrics of higher specific inductive capacity.

J. Murray Weed: The authors of these papers are to be commended for their efforts to deal in a scientific manner with subjects in which the development of design practise has been so largely the result of experimental and "cut and try" methods. Scientific treatment is to be sought for in dealing with all engineering problems. Some of these problems are so complicated, however, and the general problem of insulation is emphatically one of them, that it is necessary to urge the utmost caution in interpreting the dictates of theory. This caution needs to be exercised, not only in connection with the more complicated problems of insulation, but the danger also exists of making errors in the interpretation of the fundamental laws which affect the results in the most simple cases, such as the parallel wires, and the terminal rod and concentric ring, dealt with in the paper on "Air as an Insulator".

I cannot agree with the authors in the statement that seems to receive most emphasis as a fundamental proposition in this paper, *i.e.*,— that the maximum efficiency of air path over the surface of a solid insulator is always obtained when that surface conforms to the flux lines as they would exist if the insulator were not present. Maximum voltage for a given length of surface path will be obtained in this manner in a uniform field, (between parallel planes), but not in the field of the parallel wires, or of the rod and torus.

The cylindrical surface recommended for the parallel wires, as represented by the bottom line of the cross-hatched portion of Fig. 9 of the paper, and the surface generated by the revolution of arcs of circles for the rod and torus, as shown in Figs. 10 and 11 of the paper, may be made more efficient by flattening out the middle portions of these arcs, and using smaller radius of curvature at the ends.

Confining our attention now to the rod and torus, the explanation of this is as follows: Referring to Fig. 8, a portion of the ideal insulator recommended by the authors has been removed, giving a more nearly conical shape. That zone of the field between the surfaces *a* and *b*, the middle portion of which was occupied by

that part of the insulator which has been removed, would, if the insulator were not present, be most intense at and near the surfaces of the rod and ring. The substitution of the solid dielectric, of uniform specific capacity, throughout this zone, with surfaces conforming to the original flux lines, will not alter the distribution of the stress, although the density of the flux will be multiplied by the specific capacity of the material. As stated in the paper, the strength of the air path will remain unchanged. It will break down, however, at a much lower voltage than that corresponding to the rupturing stress in the middle portion of this field, the rupture beginning at the surfaces of the rod and ring, and extending outward as more of the total stress is brought upon the intermediate portions of the field.

If, instead of filling the entire zone between *a* and *b* with the solid dielectric, we fill only those portions adjacent to the rod and ring, where the stresses were greatest, the solid dielectric being in series in the flux path with the air further away from the terminals, where the stresses were much less, the flux density in the zone will be increased in proportion to the reduction in the total reluctance of the path. The stress in that portion of the zone still occupied by air will therefore be increased, but its maximum value may still be much lower than was the stress at the surfaces of the terminals before the solid dielectric was inserted. Since the total potential difference between the terminals does not change, the stress near the surfaces of the terminals has been reduced by the insertion of the solid dielectric, by an amount corresponding to its increase in the air in series with it. But these statements give only a first approximation to the conditions which actually exist.

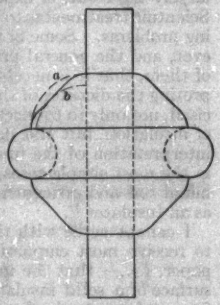


FIG. 8

This solid dielectric, in addition to being in series with air in its flux path, is in parallel with other air at the surfaces of the rod and ring in the adjacent flux paths. The reduced stress in the solid dielectric causes it to absorb some of the flux from these adjacent air paths, thus tending to equalize the stresses in these paths at the places where these stresses were maximum.

The above explanation shows how a modification of the ideal shape recommended in the paper, making it more nearly conical, by the actual removal of some of the material, and actually shortening the length of the air path, will reduce the maximum stress in the air, and increase the voltage required to break down the air path. The authors have shown merely how to place solid dielectric in the field without reducing the strength of the air path over

its surface, whereas it is possible, by a modification of the surface which they have recommended, to make a large increase in the breakdown voltage, though the length of the path over the surface is reduced.

For the purpose of proving the above deductions, the following tests were made: Insulators were turned from hard rubber, with dimensions as shown in Figs. 9 and 10. Voltages were measured by voltmeter and ratio of transformation, with a very close approximation to sine wave impressed. Three consecutive tests on the insulator in Fig. 9 gave 52.5, 53, and 52.5 kv. respectively over the surface of 3.5 cm., which is an average voltage of 15.1 kv. per cm. In like manner, three consecutive tests for the insulator of Fig. 10 gave 62.5, 62.5 and 62 kv. over the surface of 3.29 cm. This

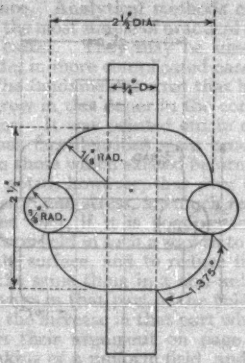


FIG. 9

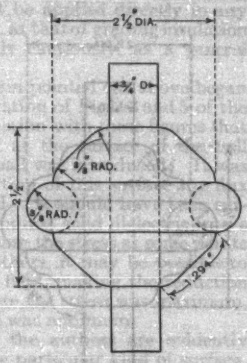


FIG. 10

average voltage per cm. was 19 kv. or about 25 per cent higher than the voltage per cm. for the insulator of Fig. 9.

Tests were also made on the insulators of Figs. 11 and 12, of same over-all dimensions as those of Figs. 9 and 10, the length of air path of Fig. 11 being 3.63 cm. and that for Fig. 12 being 4.25 cm. The average total breakdown voltages for both of these insulators was the same as for Fig. 9.

Some explanation is due for the extraordinarily uniform and high results obtained in these tests. The fit obtained between the ring and the insulator was not good, and in a preliminary set of tests breakdown occurred at about half the voltages recorded above, and was preceded by the formation of corona at the joint between the ring and insulator. It was intended to fill the crevice at this joint with paraffin, and repeat the tests, but in the meantime some tests were made of the effect of a copper shield on one

end of the rod, by redistribution of the flux. For this test the other end of the rod and insulator, to a point midway on the ring, was immersed in oil. Accidentally, the entire insulator was dipped, thus filling all the crevices with oil, which was held in the crevices by surface tension after one end of the insulator was brought above the oil again. The test gave a result like those recorded above, which was at first attributed to the shield, but a repetition of the test after the removal of the shield gave practically the same results. All of the insulators were now tested in this manner, being completely immersed in oil before the test, and then lifted so as to bring one end of the insulator and part of the surrounding ring above the surface. The oil made perfect joints between the ring and rod and the insulator, eliminating all corona, and giving uniform and consistent results.

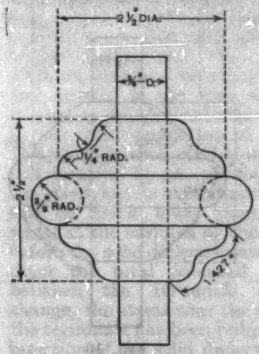


FIG. 11

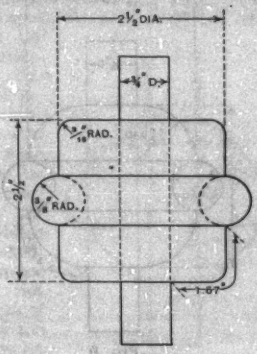


FIG. 12

No improvement was obtained with these insulators by the use of shields, or disks, for re-distributing the flux at the surfaces of the rod and ring, although several shapes were tried. On the other hand, some of the shields caused the breakdown to occur at considerably lower voltages.

In these tests, it was noticed that the oil clinging to the surface would, during the test, draw up about the rod, on top of the insulator, into a slightly elevated cone. In my opinion, this indicates a more nearly ideal form for the surface of the insulator. If we had a viscous fluid insulator, free from the effect of gravity, which could shape itself under the influence of the electrostatic field, we should see the perfectly ideal form, giving the most efficient surface for any given terminals. It is probably impractical to determine this shape analytically, even for the sim-

pler cases, but I would define it in a general way by saying that it will be obtained from the insulator conforming to the flux lines in air, recommended in the paper, by filling more of that portion of the field where the stress is greatest with the solid dielectric, and less of that portion where it is least, in such a way as to obtain as nearly as possible a uniform potential gradient over the entire surface. This will require an artist, with a good imagination, and the results of his work must be tested in comparison with the results of other similar efforts.

No one can be more in favor than I am of using analytical and scientific methods, in so far as they are applicable, in the design of insulation or insulators. It is my opinion, however, that this branch of engineering must continue to be an art as well as a science. Analytical methods cannot be applied directly in any but the most simple of practical cases, as that of grading insulation for cables. They may be used, only cautiously, as a general guide, in more complicated cases.

The fundamental error that has been pointed out above began to grow in this paper in the consideration of Figs. 2 and 5 of the paper. It was pointed out in connection with these figures that higher flux densities were produced at the surface of the ball than those which existed before the ball was introduced. It was not noted, however, that over a portion of this surface the flux density, and stress, are much reduced. It should have been surmised that, if it is possible to introduce solid dielectric into a uniform field in such a way as to increase the stress at some points on the surface, and to reduce it at others, it may be possible to do the same thing in a non-uniform field, making the reduction in stress in that part of the field where the stress was maximum, and the increase in that part where it was minimum.

In their argument on page 897, the authors are evidently thinking of a uniform field, and some particular kind of surface, as their reasoning here is not at all general.

There are some other points in this paper which deserve further consideration. For instance, in some tests which I have made, the projection R, at the middle of the spacing strip $H\,L$, in Fig. 7, has increased the breakdown voltage between the plates about 10 per cent above that obtained with straight strips (no projections). The corresponding increase in total length of surface path was 66 per cent. While the efficiency, if measured in average voltage per unit length of the path, following the contour of the surface, is considerably reduced, the voltage which can be obtained with a given distance between plates is increased.

The inference in the paper that surfaces conforming to the various flux lines of Figs. 9 to 11 (of the paper) will have equal efficiencies, will evidently not hold. The voltage gradient will be most nearly uniform, for instance, along the straight line connecting the centers of the wires in Fig. 9. The uniformity along any of the other lines will be less and less, as we pass further from this straight line, that is, with a given average stress, the maximum

voltage gradient at the surfaces of the wires is increased. The average voltage per unit length of path which will start breakdown of the air over the surface of the insulator will, therefore, be less and less, the further the surface is from the straight line or plane. On the other hand, the total volts required to produce breakdown will be greater.

The results obtained from tests of the insulators shown in Figs. 15 and 22, as reported in the paper, while striking, are easy to understand. The great length of tube at the top end of the insulator, in Fig. 15, adds a relatively small amount to the strength of this bushing, since as soon as there is over-stress over the large part of the bushing, from the tank cover to the lower end of this tube, a discharge will take place to this point, and will then travel progressively along the tube with relatively small increase in voltage.

In the case of the insulator shown in Fig. 22, the density of the dielectric field is increased at the surface of the torus by the increase in the length of the insulator, and also by the metallic shield above the insulator, since both of these things produce an increase in the flux leaving the rod, which must terminate on the ring, without any reduction in the reluctance to the flux at the end of its path adjacent to the ring. Correct design must make corresponding reductions in the reluctance at both terminals, and avoid over-stressing the air at either end, or at any point, of the flux path.

Considerations such as those given above, lead to a better understanding of the limitations of the condenser type bushing, as it is built. The layers of dielectric are so thin that, if the surfaces at the ends of these layers be made to conform to the shapes which would give the most efficient surface, whatever that shape would be, the length of the leakage path is altogether too short to stand the voltages for which they are designed. This makes it necessary to extend each of those layers a considerable distance beyond the end of the metallic layer at its outer surface, but it is not extended at the end of the flux path where the stress is maximum, *i.e.*—over the edge of the outer metallic cylinder. The increase in surface is, therefore, altogether out of proportion to the resulting increase in the total strength of the air path.

In fact, the greater these extensions, beyond a certain limited amount, the worse will be the final result for the lead. This will be understood when it is considered that the capacity between the intermediate layers of these leads is greater than that between the innermost layers, and that the extension of the varions layers presents additional surface for electrostatic flux to the tank and surrounding objects. The flux connecting the intermediate and outer layers to the surrounding objects, added to that passing through the outer layers themselves, must be supplied through the smaller capacity of the inner layers. This produces higher voltages across the inner layers. This results in the production of corona at the edges of these layers, which is cured by the use of

the very large shield at the top of the lead, as reported by the authors of the paper.

This improvement is due to the fact that the shield supplies the flux to the tank and surroundings, which otherwise originates from the surface of the lead. If, without the shield, the top of the lead (innermost layers) were not overstressed before the intermediate and outermost layers, the shield would afford no such benefit. If the top part of the lead were understressed as compared with the bottom portion, the shield at the top would be a positive detriment.

From some tests which I have made on a condenser type lead, I can say that, though the voltage distribution across the various layers of this lead were ideal in normal operation, it may be far different when subjected to a high-frequency disturbance. In these tests, high frequencies, ranging from 10,000 to 50,000 cycles, were impressed upon the lead. With about 100,000 volts across the entire lead, as measured by a sphere spark gap, the voltage across the outermost layer, measured in the same manner, was 40,000 volts. The average voltage per layer across the eight outer layers was over 14,000 volts. The average voltage over the intermediate and inner layers was about 5000 volts per layer, becoming rather higher for the inner layers. The arithmetical sum of the voltages across all of the layers was more than twice the voltage measured across the entire lead.

Referring now to the paper on "A Theorem of Electrostatics", I would say that the applications made of the theorem referred to are very interesting. No objection can be made to the forced distribution of potential illustrated in Figs. 6 to 18, except that equivalent results may be more economically obtained in other ways.

The assumption that a uniform field between parallel disks may be made to articulate with a field radiating from a cylinder, in the manner described in the paper, with reference to the condenser type lead, except by the aid of conductors connected to an external source of potential, is erroneous. This will be understood if we stop to consider that under these circumstances we would have two fluxes converging upon the conical surface of division between these two fields, *i.e.*, that of the uniform field coming downward from the upper disk, and that of the logarithmic field radiating from the lead. It is impossible for these fluxes to terminate upon this surface except by the intervention of conduction supplying current from outside sources of the proper potentials. These are, of course, actually present, in the form of the metallic layers of the condenser lead, but the fact that they are able to supply this extra current and still have the correct potential distribution, proves that this potential distribution would not be right without the shield or disk at the top, which calls for the extra current. This merely confirms the explanation given in my discussion of the other paper, that the

voltages across the inner layers of the lead are too great without the disk.

In conclusion, I wish to say that I thoroughly appreciate the serious efforts which have been made in these papers to place the design of insulators and insulation upon a rational basis, and I do not wish to discount their value. By means of investigations of this kind, combined with careful experimental work, progress will be made in the ability to design apparatus successfully and economically for high voltages. Careful study will show us, however, that the subject is by no means so simple as it has appeared in the presentation of these papers.

Harris J. Ryan (by letter): In their paper on "Air as an Insulator when in the Presence of Insulating Bodies of Higher Specific Inductive Capacity", Messrs. Fortescue and Farnsworth have isolated and well exemplified the principle that determines the proper proportions of solid high-voltage insulations so that the adjacent atmosphere will not be overstressed. This principle is applied by means of a two-fold expedient as follows:

1. Beginning with air as the insulating medium the high-voltage electrodes are so shaped that the tubes of established electric force spread a minimum. Thus the electric field is made to approach uniformity as much as practicable, and the maximum stress in the air is kept everywhere at a minimum.

2. Between the electrodes a solid dielectric is fitted and formed precisely as the tubes of electric force. Such solid dielectric is employed for a double purpose: (a) for mechanical support, and (b) to eliminate the air in the most intense portion of the electric field wherein, if it remained, it would be overstressed.

The electric field in the solid dielectric is greater than in the air displaced, by its specific inductive capacity as a multiplying factor. The voltage stresses have, however, nowhere been altered, so that the electric field, through the air surrounding the solid dielectric, remains unchanged and the stresses in it are everywhere the same with as without the presence of the solid dielectric. This is a simple expedient and the results are correspondingly certain.

We now know that a number of available solid dielectrics possess an enormous electric strength, (1,000,000 volts per cm.). Only a small part of this strength can ordinarily be utilized in practise on account of the necessary presence of air, moisture, oil and other fluids capable at comparatively low electric stresses of functioning as electrolytes, *i.e.*, as *ion carriers*. Such electrolytic or ionic conduction rapidly destroys the solid dielectric through heat and molecular erosion and not by electric overstress.

We are much indebted to the authors, who have uncovered in simplest terms the principle that controls the minimum stressing of the troublesome fluids (gaseous or liquid) in which all solid high-voltage insulators must be immersed to do their work.

Fourteen years ago, with the aid of Mr. E. F. Scattergood, use was made of the *sectored guard surface* to construct at Cornell a 90,000-volt "dry-insulated", 10-kw., 125-cycle transformer. Up to a year ago this transformer was in regular service for high-tension testing purposes in the laboratory where it was built, and it may be in use at the present time. Compared with Mr. Fortescue's thorough and effective designs for insulating very high voltage transformers our 1899 effort is of course a very crude one. However, our experience taught us to understand that one can depend upon the sectored guard surface to reduce all intense electric stresses developed in very high voltage transformers to safe working values. Other work at the time demonstrated to me the great value of the guard surface as a general expedient in high-voltage insulation. I heartily concur in the author's conclusion that "the principle is capable of wide application, and seems to afford a solution of some of the most perplexing problems confronting electrical engineers".

The results of Mr. Fortescue's own work as given in this paper abundantly demonstrate the correctness of such conclusion.

C. Fortescue: A number of important questions have been brought up in this discussion. Some of these questions indicate that further investigation along certain lines, for instance on the effect of high-frequency electric stresses on commercial dielectrics, would be of great value. Not having made any tests myself on the effect of very high frequencies on such materials as are commonly used for insulating purposes, what I say in this respect must be largely based on theoretical grounds.

Replying, then, to Mr. Thomas's first question as to the effect of frequency—if, as is assumed in the joint paper, the dielectric is homogeneous and non-conducting, the stress at any point is derivable from a potential which is a solution of Laplace's equation, provided that the applied potentials are constant. When the applied potentials are periodic, the potential is no longer a solution of Laplace's equation and the line integral of electric force taken round a closed circuit in the electric field will not be zero as in the case of a steady stress, but will be proportional to the rate of charge of the line integral of the vector potential taken round the same circuit. This relation and a similar one associating the line integral of magnetic force round a closed circuit with the rate of change of electric displacement through the circuit, are the relations from which Maxwell derived his equations for the propagation of electromagnetic waves. It is evident, therefore, that with varying potentials the potential at a point will not be a single valued function depending only upon the potentials of surrounding bodies, as in the case of steady potentials, but it will be subject to a time variation, or, to put it another way, the equipotential surfaces will change in form during the cycle. With slow cyclic changes in potential this effect will be negligible, but with very high frequencies it cannot

be ignored. Another factor that is negligible at commercial frequencies but becomes of great importance at high frequencies is molecular loss in the dielectric. With sustained high frequency these losses may, by the effect of local heating, ultimately produce breakdown.

The proper remedy for both these conditions is to be found in the method of designing insulators outlined in the joint paper, that is, to so design the insulator as to have as near uniform stress as possible over the surface, under normal conditions, and allow a liberal factor of safety to take care of abnormal stress conditions.

Replying to Mr. Thomas's second question as to the effect of external bodies—the remedy appears to me to be obvious, namely, to make the electrodes of the insulator of such a form that they will shield the surface of the insulating body from external influence. In other words, the electrodes must be designed so that the field between them will be but slightly affected by external bodies. In some cases, as for instance in outlet terminals, external bodies form one of the electrodes. The case cited by Mr. Thomas is one of these and the large plane on top of the terminal only completes the design of the terminal according to the premises assumed, as is fully explained in the second paper.

Regarding the matter of conduction over the surface, which is the subject of Mr. Thomas's third question, I have observed that soot is precipitated from the atmosphere wherever there is corona. Corona is probably present under working conditions in nearly all the present forms of commercial insulators, which accounts for conduction over the surface being considered of so much importance in these designs. It may be well to add that corona itself causes conduction and therefore in such insulators, even when free from dirt, there may be conduction over parts of the surface. In the forms of insulators discussed in the first paper corona is entirely absent up to the breakdown point. Thus there is no conduction over the surface due to corona itself and no tendency for smoke to be precipitated over the surface in the form of soot. The test piece exhibited has been tested with three months' natural deposit of Pittsburgh dirt and its strength was unimpaired.

The presence of corona will, I believe, always tend to weaken the air in the neighborhood of an insulator, and therefore should be avoided if possible. When corona is present in an insulator or air gap, as the potentials are increased at the electrodes the outer surfaces of the corona formation will advance, the maximum intensity at the surface of the formation remaining unchanged until the formation reaches a certain critical point, the form of the electric field for which is such that further formation cannot take place without an increase in the flux intensity; this is the point of breakdown. Even at this point arcing may not actually take place, on account of the high resistance of the corona, but

breakdown is manifested by the presence of streamers or sparks passing between the electrodes. When the electric field is nearly uniform the introduction of any disturbing element, such as that illustrated in Fig. 7, will cause breakdown at a very much lower value than if the disturbing element were absent. This proposition has been demonstrated by actual tests.

I have in a previous part of this discussion shown that air insulators of the type under discussion may be designed so as to be inappreciably affected by external bodies. By way of answer to the latter part of Mr. Thomas's discussion it may be well to add that with a proper design and suitable factor of safety there would be less likelihood of trouble with the ideal form of distribution than with the other.

I wish to say in reply to Mr. Thomas's last question that there is no reason why a million-volt transformer with two terminals of opposite polarity should not be made. The transformer described in the second paper, from an insulation standpoint, is the equivalent of such a transformer. The point I wanted to bring out in this paper is that two 500,000-volt transformers with one end grounded, is a better proposition for a test room then one one-million-volt transformer with terminals of opposite polarity, because the majority of tests are made with one end grounded, and with the first proposition two transformers are available for testing purposes. These two transformers when connected in series in the primary are exactly equivalent to the one-million-volt transformer.

Mr. Mershon's questions as to the effect of high frequency, dirt and the presence of neighboring bodies, are answered in my reply to Mr. Thomas's questions.

The scheme of Fig. 3 referred to by Mr. Mershon was suggested by Mr. Chubb. The causes of the discrepancies in the results are several; possibly one of them is that suggested by Mr. Mershon. Others are the effect of the sides of the tank and the effect of the ends of the cylinder. The equipotential surfaces given are only a first approximation to the true surfaces with an infinitely long cylinder passing through a ring.

I am glad Mr. Mailloux called attention in his discussion to the great gains that have been made in the past by the use of theory. The remark is often heard that practise and theory do not agree. This attitude of mind is so ingrained in some that when they come across such a case of apparent disagreement, instead of looking into the matter and finding the cause of it, they accept it as a further proof of the unreliability of theory. Whereas, if it were early instilled in the minds of these men that theory and practise are not antagonistic, but that disagreement between them is the result either of incorrect observation or of incorrect or incomplete premises, far greater progress would be made.

I think with Mr. Peek that the theory of electric stresses is generally very inadequately presented in engineering courses. Too much stress is laid on charges and distribution of charges

when potentials and distributions of potentials are the determining factors in practical application.

Messrs. Thomas and Peek lay great stress on the possibilities of disastrous effects due to high frequency. I think this matter of high-frequency surges is a good deal of a bogy. The number of failures of transformers attributed to high-frequency surges that have come within my observation during the past ten years has been so small that this factor has not appeared to me to be of much consequence as a cause of failure. However, as I have already pointed out, there is no reason why an insulator or transformer designed according to the principles given in the two papers should not at the same time be capable of withstanding high-frequency oscillations, and as a matter of fact these conditions are taken into account in the design.

Mr. Peek's remarks on the insulator shown in Fig. 20 seem to indicate that he has not read the second paper carefully or else he has not grasped the principle stated. Reasoning from Mr. Peek's point of view the condition for equal division of potential between the units of an insulator is that the flux leaving each electrode shall be the same; this means that the capacity of each electrode to ground must be inversely as its potential. This condition is approximated very closely if the high-potential and ground-potential electrodes coincide at their edges with two large parallel disks as shown in Fig. 20. The advantage of this method of obtaining equal distribution of potential over that suggested by Mr. Peek has already been pointed out in the paper.

Dr. Kennelly's remarks as to the importance of having a name for the electrostatic unit of flux are very interesting. When dealing with alternating stresses it is always necessary to indicate whether maximum or root-mean-square values are intended. This ambiguity would not exist if the flux density were given instead.

In reply to Mr. Weed's strictures on the joint paper, I wish to say that it was not the intention of Mr. Farnsworth and myself to give out as a fundamental proposition that the surface conforming with the flux lines that would exist if the insulating body were removed gives maximum efficiency. The investigation was undertaken to show that the breakdown voltage over the surface of an insulator depends on the strength of air. The authors came to the conclusion that creepage actually existed in most insulators on account of corona set up at the surface of the insulator due to the deflection of the flux from the air into the insulator. The natural remedy for this is to make the surface of the insulator conform to the flow lines that would exist in air alone between the two electrodes. By properly shaping the electrodes the breakdown path may be made very efficient. I agree with Mr. Weed that slight changes from this form may sometimes result in slightly higher efficiency, but on the other hand a radical change will result in lower efficiency. If the electrodes are shaped to give a good field, then the surface conforming to the flow lines will conform very closely to the best form.

It would take too long to discuss all the points brought up by Mr. Weed, particularly since the greater part of them are based on a misunderstanding of the object of the paper. There is one point, however, in his discussion of the joint paper, that should be answered, and that is his report of a test he made to determine the truth of the statement as to Fig. 7 of our paper. The plain strip used by him should give a breakdown value equal to that between the plates when only air is present, otherwise the results are valueless. I do not think Mr. Weed's tests are as conclusive as he seems to consider them. Other observers independently of ourselves have obtained results that agree with our conclusions.

Mr. Weed's remarks about the condenser type terminal are merely a recapitulation of what has been said in the two papers in a more general way. I do not think Mr. Weed can have read over the second paper with care, otherwise he would not have found any such assumption as he indicates in the paragraph preceding the last in his discussion. It is particularly pointed out in this paper that in order to obtain the proper conditions of stress in a condenser type terminal the edges of the high-potential and ground-potential cylinders must be on two infinite parallel planes, but, as pointed out in the paper, even then the conditions will not be ideal, on account of the number of steps being finite, but practically the division of potential will be uniform at ordinary frequencies. The reliability of the condenser terminal has been conclusively proved in service.

A Series of Lectures before the American Institute of Electrical Engineers, New York, March 19, 26, April 2, 9, 16, 1913.

Copyright 1913 By A.I.E.E.

RADIOACTIVITY

BY EDWIN PLIMPTON ADAMS

LECTURE I

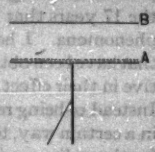
The science of radioactivity has now reached a stage in its development at which we can speak of it with a good deal of confidence. Among those who feel a keen interest in the recent developments of science, but who have not had time to follow them in detail, and it is to such that I was asked to address these lectures, there is a rather prevalent feeling that the discoveries in this branch of physics and chemistry have been of a revolutionary character. One often hears the opinion expressed that the discoveries in radioactivity have completely overthrown many of the theories that we had come to look upon as firmly established. In particular, I have often been asked about the validity of the principle of the conservation of energy—the fundamental principle of the physical sciences—in the light of the phenomena of radioactivity. Can we still build upon that principle? What I shall attempt in these lectures is to show how far our old notions of the constitution of matter are still valid, what modifications we must make in them, and where the physical sciences stand at present in the light of the discoveries that have been made during the 17 years that have elapsed since the discovery of radioactive phenomena. I hope to succeed in showing you that the results that have been obtained are much more constructive than destructive in their effect upon our views as to the constitution of matter. Instead of being revolutionary in their tendency they lead, viewed in a certain way, to a logical development of the physical sciences; for these discoveries give us information about the interior structure of the atom about which everything was largely conjecture. We are only at the beginning of what is bound to lead to a much fuller conception of atomic structure. The foundation for it has

been built up, and it is this foundation that I wish to describe to you.

The discovery of the property of radioactivity may be said to have had its inception in the discovery by Röntgen, in 1896, of the rays which bear his name. Guided by the similarity between the greenish yellow luminescence observed on the walls of a Röntgen ray bulb when the rays are produced and the greenish phosphorescence of certain uranium compounds after exposure to light, Becquerel sought a connection between these two phenomena. In the course of his experiments Becquerel found that uranium and its compounds produced effects very similar to those of the Röntgen rays—namely, a photographic plate completely shielded from ordinary light, by covering with black paper, was affected when the uranium was brought near in the same way that it would have been if exposed to ordinary light; and furthermore, the air in the neighborhood of the uranium became a conductor of electricity. But there is one striking difference between the effects produced by these two agents. For the Röntgen rays to produce them there must be a continuous supply of energy from outside to keep the electrical discharge in the bulb; while the production of these effects by the uranium was found to depend in no way upon previous illumination or any other external source of energy.

Becquerel thus discovered a new property of matter—the property of radioactivity, and it was an important question to determine whether this property was exhibited by other substances than uranium and its compounds.

In the first place it must be shown how the radioactivity of different substances may be compared. The property which is generally made use of for this purpose is that of rendering air a conductor of electricity. As the currents to be measured are very small, smaller than can be measured by a galvanometer, some form of electrometer is employed. The simplest is the gold leaf electroscope.



Let A and B be the plates of a condenser of capacity C. A known amount of the radioactive substance is spread on A. If charged to a difference of potential V the quantity of electricity on one of the plates is $C\ V$. The current flowing between the plates is

$$C\frac{dV}{dt} = i$$

Suppose that over a certain range of motion of the gold leaf it is known that a fall in its potential of a volts corresponds to a fall through θ degrees. Then a fall through ϕ degrees in a second will correspond to a current

$$i = \frac{a\,C}{\theta}\,\phi$$

The electric current through the air does not obey Ohm's law, but exhibits the phenomenon of saturation; *i.e.*, as the difference of potential is increased from 0, the current first increases nearly proportionately to the potential, rising to a nearly constant value which it keeps until the difference of potential is sufficient for a discharge to take place. As long as the difference of potential is greater than a certain value (100–200 volts in usual cases) the currents measured in this way will be nearly the same over a very wide range of potential difference.

Now Becquerel found that the activity of the different compounds of uranium was proportional to the amount of uranium contained in them. If the activity of metallic uranium be taken as unity, then the activities of the uranium compounds will be expressed by numbers less than unity.

Of the elements known at that time, only one other was found to have radioactive properties. Schmidt and, independently, Madame Curie, found that thorium and its compounds were radioactive.

Madame Curie's discovery of the radioactivity of thorium was made in the course of a systematic investigation, first, of all the known elements it was possible to secure, and then of a large number of minerals and rocks. She found that the activity of the uranium minerals was larger than was to have been expected from their uranium content. Thus a certain specimen of pitchblende, an oxide of uranium, had an activity nearly four times that of metallic uranium. An obvious deduction from this discovery was that these minerals contained one or more hitherto unknown substances, in minute proportions to have escaped discovery by chemical analysis and of correspondingly high radioactivity.

The method employed by Madame Curie to test this hypothesis was to subject a large quantity (one ton) of the residues from the mineral pitchblende, after the uranium had been extracted, to chemical analysis. It was found that the radioactivity of these

residues was four times as great as that of metallic uranium, from which it was concluded that the greater part of the conjectured substance was contained in them. In brief, the method of attack consisted in measuring the activity of all the products of a chemical separation in order to find which one of them included the looked-for substance. This one was then subjected to further separation and the process continued. The difficulties in this procedure were great, for owing to the phenomenon of induced or excited radioactivity, of which more will be said later, there was some uncertainty in the earlier stages of the separation as to which product contained the radioactive substance; and, in addition, it was found that there were several unknown substances, strongly radioactive, of different chemical behavior, which complicated the search very considerably. But we shall see that all these substances are closely related so that for the present it will be sufficient to speak of only one of them.

It was finally found that the product of separation containing the barium was enormously more active than any of the other products. No chemical method of making a further separation could be found, and so recourse was had to an assumed difference in solubility between the barium salt and the unknown substance. From a solution of two different substances that one of less solubility will crystallize first. The barium in the form of barium chloride was allowed to crystallize and the first crystals formed were found to be decidedly more active than those found later.

One of the characteristics of an element is the possession of a definite spectrum. When this very active barium chloride was examined spectroscopically before the fractional crystallization began, only the lines due to barium appeared. As the process of fractional crystallization proceeded new lines appeared, the barium lines grew fainter, until after a number of crystallizations the original barium spectral lines had disappeared, and a new spectrum had taken their place. This in itself was sufficient to prove the discovery of a new element, to which the name radium was given.

From a ton of the original material 120 milligrams of radium chloride were obtained in the way indicated. Its activity was estimated by Madame Curie at about a million times that of uranium. Madame Curie also succeeded in determining the atomic weight of the new element radium. The first number obtained, 225, has been corrected by more recent work, so that now 226.4 is accepted as the atomic weight of radium, taking oxygen = 16.

There being a greater difference in the solubilities of radium and barium bromides than of their chlorides, radium is now generally prepared in the form of the bromide.

Madame Curie and Debierne have lately been successful in isolating the metal radium itself by electrolysis with a mercury cathode, thus forming a radium amalgam. This amalgam was then distilled in an atmosphere of hydrogen. The mercury was completely driven off at a temperature of 700 deg. and the remaining substance, practically pure radium, had a shining white metallic luster. It rapidly turned black in air, and decomposed water. Chemically its behavior was thus similar to that of metallic barium.

We have now traced, very briefly, the processes leading to the discovery of this new element radium, and we must now study the physical properties of it in greater detail. We have seen that one of its most striking properties is that of rendering the air surrounding it a conductor of electricity. It will therefore be well to preface this study by a brief resumé of the theory of ionization of gases.

A gas in its normal condition is a non-conductor of electricity. It may be made a conductor by various agents, among others, the passage through it of Röntgen rays, of ultra-violet light, and, we have seen, by radioactive substances. But it was through the study of the electric discharge in vacuum tubes that our knowledge of the way in which gases become conductors of electricity came; and to Sir Joseph J. Thomson belongs the credit of having developed a consistent theory which has proved of the greatest service in all the recent developments of electric theory.

The leading idea in Thomson's theory is that negatively charged corpuscles—or electrons—are shot out from the cathode; that these corpuscles by their collisions with the neutral molecules of the gas ionize them; that is, split them up into positive and negative parts; the positive ions travel towards the negative electrode, the cathode, and the negative ions towards the positive electrode, the anode. We thus have a double transport of electricity through the gas—positive electricity in one direction and negative electricity in the opposite direction. This constitutes an electric current, flowing in the direction of the positive ions. The path of the cathode rays, the stream of corpuscles shot out from the cathode, is made visible by the light which is produced in the ionization of the gas molecules, and there is also

a greenish yellow luminescence produced where the corpuscles strike the walls of the tube. An obstacle placed in the path of the cathode particles casts a shadow on the walls of the tube. By placing a diaphragm with a small opening in front of the cathode, a narrow beam of the cathode rays may be separated. When a magnet is brought near, the beam is deflected in the direction that a stream of negatively charged particles shot out from the cathode should be. The negative charges carried by these corpuscles may also be demonstrated by bending the beam into a vessel connected to an electrometer which becomes negatively charged. In short, every test that may be applied shows that the cathode rays are a stream of negatively electrified corpuscles. The cathode particles have one striking property which at first caused many investigators to doubt their material nature. This is their ability to penetrate thin sheets of metal and other substances. But now that we know their very high velocity, this property is not so surprising. The sudden increase in the electric current through a gas which occurs when the potential difference rises to a certain value, the "sparking potential," receives a ready explanation in this theory. The ions produced from the gas molecules are under the influence of the electric field. If the electric field is strong enough it will give the ions a sufficiently high velocity so that they become ionizing agents themselves—producing fresh ions by their collisions with the molecules of the gas.

The real confirmation of the hypothesis of the material nature of the cathode particles was furnished by actual measurements of their velocity, the charges they carry, and their mass. As the same methods have since been employed in the study of the radiations from radioactive substances, we may well devote a little time in considering the principles involved in such measurements.

Let us suppose that we have a corpuscle of mass m, charged with e units of electricity and moving in a straight line with uniform velocity v. As proved by Rowland's classic experiment, a charged body in motion is equivalent to an electric current. Suppose that a magnetic field of intensity H is set up in a direction at right angles to the motion of the corpuscle. If there were an electric current, i, flowing along a wire in the path of the corpuscle, we know that on each element of length ds of the current there would be a mechanical force $H\,i\,ds$, this force being perpendicular both to ds and H. The current element $i\,ds$ is to be replaced

by the product of the charge and its velocity, $e\,v$. So that the force acting on the corpuscle at right angles to v is $H\,e\,v$. The acceleration normal to the velocity is v^2/ρ where ρ is the radius of curvature, or in our case the radius of the circle into which the path of the corpuscles is bent. We thus have

$$H\,e\,v = \frac{m\,v^2}{\rho} \tag{1}$$

Let us next suppose that an electric field of intensity X is set up parallel to the magnetic field, at right angles to v and to H. This exerts a force $e\,X$ on the corpuscles, and by varying X we can make this force just balance the force exerted by the magnetic field so that the corpuscle will be undeflected. We then have $H\,e\,v = e\,X$

or

$$v = \frac{X}{H} \tag{2}$$

which determines the velocity of the corpuscles, and by (1)

$$\frac{e}{m} = \frac{X}{H^2\,\rho} \tag{3}$$

which determines the ratio of the charge to the mass of the corpuscle. In these expressions X and H may be determined by the usual methods of measuring electric and magnetic forces. To determine ρ, it is necessary to measure the displacement of the spot of light made by the narrow beam of cathode rays on a phosphorescent screen when the magnetic field is applied; by geometry the radius of the circular path may then be found.

The velocity of the cathode particles found in this way was as high as 1.2×10^{10} cm. per second, roughly one third the velocity of light. Probably the most accurate value of e/m found by this method is 1.8×10^7 when the charge is measured in electromagnetic units. It is interesting to compare this with the ratio e/m for the charge carried by a hydrogen atom in the electrolysis of water. Let N be the number of molecules in one cu. cm. of gas at 0 deg. cent. and at 760 mm. of mercury. If e is the charge on an atom of hydrogen $2\,N\,e$ is the whole charge in one cu. cm. One electromagnetic unit of electricity liberates 1.04×10^{-4} grams of hydrogen. If m is the mass of hydrogen atom $2\,m\,N$ is the mass of one cu. cm. of hydrogen. So that

$$\frac{e}{m} = 9.6 \times 10^3$$

We shall show that there is strong reason for believing that the charge on a corpuscle is the same as the charge carried by an atom of hydrogen in electrolysis. The mass of the hydrogen atom, which was, up to the time of the discovery of corpuscles, the smallest mass known, is thus seen to be about 1800 times greater than the mass of a corpuscle.

Measurement of the Charge Carried by Ions

We have seen that the cathode particles have the power of ionizing gases through which they pass. This process consists in the splitting up of an atom or molecule into a positively and a negatively charged ion. Now it was discovered by C.T.R. Wilson that these ions act as centers of condensation for water vapor. In perfectly dust-free air, saturated with water vapor, no cloud of water drops will form unless the air is suddenly cooled by an expansion to something like eight times its initial volume. But if dust is present very much smaller expansions will suffice to produce a visible cloud on expansion. Wilson discovered that in dust-free ionized air sudden expansion to 1.25 the original volume was sufficient to produce a cloud in the air, each ion presumably becoming the nucleus of a water drop. These drops fall under gravity and their rate of fall may be determined from the rate of subsidence of the top of the cloud after the expansion has taken place. A calculation, by Stokes, gives as the rate of fall of a sphere in a fluid

$$v = \frac{2}{9}\frac{g\,a^2\,\rho}{\mu}$$

g being the acceleration due to gravity, a the radius of the drop, μ the coefficient of viscosity of the fluid, air in our case, and ρ the density of the sphere. This expression thus enables us to determine the radius of the water drops. The whole volume, q, of the water vapor deposited per unit volume may easily be determined by thermodynamical methods; and

$$q = \frac{4}{3}\,n\,\pi\,a^3$$

where n is the number of drops per unit volume. This enables us to determine n, which, if we assume that each ion acts as a nucleus for one drop, gives us the number of ions per cubic centimeter. The total charge carried by all the ions of one sign

may be determined by measuring the current through the air when a potential difference is applied; then the charge on a single ion is deduced at once.

This method was modified by H. A. Wilson so as to eliminate many of the uncertainties inherent in Thomson's original method. The cloud was produced between the plates of a parallel plate condenser and the rate of motion of the top of it observed alternately when under the influence of gravity only, and when in addition an electric field was applied. The force on the drop due to the electric field is $X\,e$ and due to gravity

$$\frac{4}{3}\pi\,\rho\,g\,a^3$$

$$\frac{X\,e + \frac{4}{3}\pi\,\rho\,g\,a^3}{\frac{4}{3}\pi\,\rho\,g\,a^3} = \frac{v_1}{v}$$

v_1 is the velocity when an electric force is applied; v, with no electric force.

$$v = \frac{2}{9}\,\frac{g\,a^2\,\rho}{\mu}$$

$$e = \sqrt{2}\,g\,\pi\sqrt{\frac{\mu^3}{g\,\rho}}\,\frac{v^{3/2}\,(v_1 - v)}{X\,v}$$

Another modification, in which the motion of a single drop is watched, was made by R. A. Millikan, and the results of his measurements are probably the most accurate that we have. In the two methods we have sketched the cloud must be observed immediately after its formation, since it rapidly disappears by evaporation. Millikan used oil drops, formed by means of an atomizer and blown into a chamber from which they dropped through an opening into the space between the plates of a parallel plate condenser. This space could be made airtight after a drop had fallen into it so as to prevent air currents disturbing the motion of the drop. The oil drop was specially illuminated and was observed through a telescope. In its formation the drop became charged with frictional electricity so that its motion could be controlled by the electric field in the air condenser. The evaporation from it was so small that a single drop could be

observed for several hours. An ionizing agent, Röntgen rays or radium rays, acted on the air in the condenser and the oil drop occasionally picked up an ion. The instant it did so its motion suddenly changed, and from the change in its motion the magnitude and sign of the charge it had picked up could be found. In addition to the more accurate method of observing, Millikan employed a correction to Stokes's formula for the rate of fall of a sphere in air which was developed by Cunningham for the case of very small spheres. The results of Millikan's experiments were that the charges on the oil drops were always exact multiples of an elementary charge, that is, the oil drop picked up one or more of these elementary charges. Its magnitude was found to be $e = 4.774 \times 10^{-10}$ in electrostatic units.

We have seen that determinations of the velocity and the ratio e/m have been made directly on the corpuscles forming the cathode rays. On the other hand determinations of e, the elementary charge, have been made only on ions, both positive and negative, which are formed by various ionizing agents. The evidence that the cathode particles carry this elementary charge is perhaps not conclusive, but the fact that the ratio e/m is found to be the same for the corpuscles however they are produced, and that ionization in certain cases must be considered as the result of a corpuscle entering into a neutral atom, thus giving the ion the charge of the corpuscle, gives us very strong reasons for believing that all corpuscles carry this negative elementary charge.

The accurate determination of the charge on an ion leads to a knowledge of many important physical constants. It is known by experiment that when 1 electromagnetic unit of electricity is passed through water 1.04×10^{-4} grams of hydrogen are liberated. If N is the number of molecules in a cubic centimeter of any gas at a pressure of 760 mm. of mercury, and at 0 deg. cent. temperature, ρ the density of hydrogen, and e the charge on a hydrogen atom in electrolysis,

$$2 \frac{N e}{\rho} 1.04 \times 10^{-4} = 1$$

or

$$e = \frac{\rho\, 10^4}{2.08\, N}$$

Now N may be estimated from the results of the kinetic theory of gases. The value of N so obtained is, on the average,

$$N = 3 \times 10^{19}$$
$$\rho = 9 \times 10^{-5}$$

from which it follows that

$$e = 1.4 \times 10^{-20}$$

in electromagnetic units or

$$4.2 \times 10^{-10}$$

in electrostatic units.

This is so near the value of the charge in the ion, determined in the way sketched above, that we are led to believe that the charge on the ion of hydrogen in electrolysis is equal to the elementary charge determined on gaseous ions. As the latter determination is one in which we have more confidence than estimates based upon the kinetic theory of gases, we are led to determine N from the known value of e. This gives

$$N = 2.7 \times 10^{-19}$$

Now if m is the mass of an atom of hydrogen

$$m = \frac{\rho}{2\,N}$$

Thus the mass of an atom of hydrogen is

$$1.67 \times 10^{-24}$$

and from this the mass of the atom of any element can be determined from its atomic weight in terms of hydrogen as unity.

Radiations from Radioactive Substances

We now are going to consider the radiations from radioactive substances in particular. To trace in detail the course of the discovery of the nature of these radiations would require too much time, and so we must limit ourselves to an outline of what is known about them today and the evidence upon which our knowledge rests.

Beta Rays. We consider first the so-called beta rays. These rays are in all respects identical with the corpuscles forming the cathode rays in a vacuum tube, except that, among them, there are some that travel with very much higher velocities than any that can be produced in a discharge tube. Their equivalence to the cathode corpuscles is shown by measurements of e/m and v for them—measurements that are made in exactly the same way, by magnetic and electric deviation, as for the cathode particles. Further, the charges on the ions produced by them are also the same as the charges on the ions produced in any other way. Later

on we shall have to speak of a variation of the ratio e/m with the velocity, but it is a variation which is conditioned only by the velocity and does not indicate that these corpuscles themselves are in any way different from the others.

To show the penetrating power of the beta rays, as well as the charge they carry, Strutt devised a striking experiment. A quantity of radium in a thin-walled glass tube was supported by an insulator inside a highly exhausted bulb. The beta rays penetrated the glass tube, leaving the radium positively charged. A pair of gold leaves was carried by the glass tube containing the radium, and by means of a wire sealed into this tube the gold leaves were kept at the same potential as the radium. As the radium gained a positive charge by the expulsion of the negative corpuscles the gold leaves diverged until they touched the walls of the bulb which were coated with tinfoil, connected to earth. They then discharged to earth, and collapsed. This process repeated itself over and over again.

On passing through matter the velocity of the beta particles is reduced. For this reason, even if it should be assumed that all the beta particles from a given radioactive substance are emitted with the same velocity, those which are emitted from a thick layer of substance will have different velocities, since they pass through different thicknesses of the substance. The most rapidly moving beta particles have velocities very near the velocity of light, differing from the latter by about one per cent. It is not surprising, therefore, that they should be able to penetrate considerable thicknesses of solid matter. W. Wilson found that on passing through 2 mm. of aluminum the velocity was reduced from 2.86×10^{10} cm. per second to 2.00×10^{10} cm. per second.

In their passage through matter the beta rays lose their energy. In gases this loss of energy is caused by ionization, as it requires work to form ions from neutral atoms. In solids, also, there is good evidence that their conductivity is increased by the ions formed in them by the beta rays. The rays thus have their energy decreased so much that ultimately they are unable to ionize the atoms through which they pass.

Some very remarkable results have recently been obtained by C. T. R. Wilson, who succeeded in photographing the paths of the beta particles through gases. In passing through a gas positive and negative ions are formed, and these ions act as centers of condensation of water vapor. The path of a beta particle is thus marked out by the water drops formed on the ions which it pro-

PATHS OF BETA PARTICLES [ADAMS]

PATHS OF ALPHA PARTICLES [ADAMS]

duces, and with great ingenuity and experimental skill Mr. Wilson has succeeded in obtaining photographs of these trails of water drops. Two of his photographs are reproduced here. I am indebted to Mr. Wilson for permission to use these photographs. The beginnings of the trails are quite straight and very faint, showing that the velocity of the beta particle is so high that it passes through the molecules without ionizing many of them. As the velocity decreases, more ions are formed, and the path of the beta particle becomes curved as a result of deflections arising from collisions with the molecules.

Alpha Rays. Another type of radiation emitted by radioactive substance is made up of the alpha rays. These differ from the beta rays, first, in that they are positively charged, carrying charges double that of the beta particles, and in that their mass is that of an atom of helium. They produce ionizing and photographic effects like the beta particles, but their very much larger mass and their lower velocity account for their smaller penetrating power.

The alpha particles from any given radioactive product are all emitted with the same velocity. This makes the study of their absorption in passing through matter simpler than for the beta particles, which are emitted in groups having different velocities. The fastest particles are emitted with a velocity of 2.22×10^9 cm. per second while the slowest have an initial velocity of 1.45×10^9.

It was found by Bragg that the alpha particles on traversing matter are slowed down, and when their velocity falls below a certain value they lose their ionizing and photographic power. The "stopping power" of various substances is found to be proportional to the square root of the atomic weight. For chemical compounds, it is proportional to the sum of the square roots of the weights of the atoms contained in the molecule.

An interesting effect produced by alpha rays is the so-called scintillation phenomenon observed when the alpha particles strike against a screen of phosphorescent zinc sulphide. The screen appears, when looked at through a magnifying glass, to be dotted over with points of light, which come and go in a wholly irregular manner. This effect is probably caused by the mechanical impacts of the alpha particles producing changes in the crystalline structure of the zinc sulphide—analogous to the glow observed when a lump of sugar is broken in the dark. It is found that when the velocity of the alpha particles falls below its limiting value for producing ionizing and photographic effects, the scintillations

also cease. These scintillations may be counted, and, assuming that each point of light is caused by the impact of one alpha particle, an estimate may be made of the rate of emission of alpha particles from various radioactive substances. But a more certain method of arriving at the same result was devised by Rutherford. A small opening was made in a chamber in which a strong electric field was maintained. The alpha particles are shot out in all directions from a radioactive substance, so that the ratio of those entering the opening in a given time to the whole number shot out in the same time was known from the geometry of the arrangement. On entering the chamber the alpha particles produced ions and thus an electric current was suddenly started in the chamber, which disappeared very quickly as the ions were removed by the electric field. Thus the entrance of each alpha particle into the chamber was marked by a sudden rise in the current flowing through it, and this was made known by the kick of the electrometer needle used to measure the current. The number of kicks in a given time gave the number of alpha particles entering the chamber in that time, and from this the whole number of alpha particles emitted could be deduced. As a single alpha particle does not produce ions enough to give a current which can be detected, the current was multipled by fresh ions produced by the action of the strong electric field on those already present.

Knowing now the whole number of alpha particles emitted from a radioactive substance, the charge on each is known as soon as we know the whole charge carried by the particles. Measurements of this kind have been made by Rutherford and others, and the results show that the alpha particle carries a charge opposite in sign but double the amount of the charge carried by the beta particle, or electron.

From the deflection of a beam of alpha particles in an electric and a magnetic field the ratio e/m, and the velocity v, have been determined. Knowing now the charge, e, the mass of a single alpha particle is known at once. The ratio e/m is the same for the alpha particles from all the radioactive substances, while their velocity is different. In this way it is found that the alpha particle has a mass equal to four times the mass of the hydrogen atom. This is very nearly the mass of the helium atom and it thus seemed that the alpha particle was a helium atom which had lost two negative corpuscles, leaving it effectively charged with a double positive charge. This hypothesis was put to the

PATHS OF ALPHA PARTICLES [ADAMS]

PATHS OF ALPHA PARTICLES [ADAMS]

PATHS OF BETA PARTICLES [ADAMS]

The broad line is the path of an alpha particle.

test by Rutherford. The alpha particles were allowed to penetrate through the very thin walls of a glass tube into a highly exhausted tube through which an electric discharge could be passed. By examining its spectrum the nature of the gas, if any, which collected in the tube could be determined. In a few days the whole spectrum of helium appeared. Control experiments precluded any other possibility than that the alpha particles, shot through the walls of the tube, and having their charge neutralized, became helium atoms. The special significance of this fact will be spoken of later when we come to consider the disintegration theory of radioactivity.

The recent experiments of C. T. R. Wilson, making visible the tracks of the beta particles through a gas by photographing the water vapor which condenses on the ions produced, have been spoken of. He obtained similar results with the alpha particles. His photographs, some of which are shown here, are even more striking than those obtained with the beta particles. The alpha particle, owing to its greater energy, is a much more efficient ionizer than the beta particle so that its track through a gas is marked out by many more ions on which the water drops collect. It will be seen that these tracks end abruptly, and this is accounted for by the fact that they have a definite range, beyond which their ionizing power ceases. Many of the tracks show a bend toward their end. This is probably the result of the reduction in their velocity which makes them more easily deflected from their straight line motion by collisions with the molecules.

Gamma Rays. The third distinctive type of radiation emitted by radioactive substances is the gamma radiation. There is no direct evidence, as in the case of the alpha and beta rays, that the gamma rays are formed of charged particles. The gamma rays produce photographic and ionizing effects; their most striking property is their relatively enormous penetrating power. A thickness of about two millimeters of lead is sufficient to absorb all the alpha and beta particles emitted by radium. Effects produced by gamma rays have been observed after they passed through 30 cm. of iron.

To account for the gamma rays there are two theories we must consider. The first is the ether pulse theory which was originated by Stokes to account for the Röntgen rays. When a charged particle is in uniform motion through the ether there is no radiation of energy from it. Once get it moving and it will continue to move in a straight line with constant velocity. Accompanying

a charged particle at rest, there is an electric field which is everywhere directed along the radius drawn from the particle. In other words, lines of force go out from it, if positive, and enter it, if negative, equally distributed in all directions. There is no magnetic force while the particle is at rest. Now suppose the particle moves with uniform velocity in a straight line. It carries its lines of force with it, and as long as the velocity is small there is not much change from the equal distribution of lines in all directions. A charged particle in motion acts as an element of current; so that there is a magnetic field accompanying it. The magnetic force is at every point perpendicular both to the direction of motion and to the line drawn from the particle to the point. It is thus everywhere perpendicular to the electric force. Now, for higher velocities, the lines of electric and magnetic force crowd towards the equatorial plane, always at right angles to each other. For a velocity equal to that of light the electric and magnetic forces would all be concentrated in the equatorial plane.

Suppose now that a charged particle, moving with a velocity very nearly equal to that of light, is brought to rest within a very short distance by collision with an atom or by any other means. Just before its collision it carried a field of electric and magnetic force with it and this field was concentrated near the equatorial plane. Now suppose that the corpuscle is brought to rest in a very short distance. A pulse of intense electric and magnetic forces, at right angles to each other, spreads away from the corpuscle with the velocity of light, the direction of propagation being normal to the electric and magnetic forces. The thickness of this pulse is proportional to the distance in which the stopping took place, that is, to its acceleration. A succession of such pulses arising from the stopping of many corpuscles will thus give rise to electromagnetic waves in the ether which differ in no respect from waves of light except that the wave length is much less than that corresponding to light of the shortest wave length that we know anything of. On this view, the gamma rays from radioactive substances and the Röntgen rays are identical in their nature. Differences in effects produced by these two radiations are to be expected, since the beta rays, the origin of the gamma rays, have velocities which are much greater than the cathode rays which give rise to the Röntgen rays.

The other view as to the nature of gamma rays is due to Bragg. He regards the gamma rays as made up of material particles, a

negative corpuscle united to an equal positive charge, so that the combination is neutral electrically, the whole travelling with a velocity very nearly equal to that of light. This view of the gamma rays explains as well as the pulse theory the absence of any deflection of the gamma rays by electric or magnetic fields; it was originated by Bragg to account for certain dissymmetries on the incident and emergent sides of matter through which the rays pass—effects which are difficult to account for on the ether pulse theory. The study of the whole matter is greatly complicated by the secondary rays produced when gamma rays fall upon matter; these secondary rays are partly secondary gamma rays and partly secondary beta rays.

On the whole, the evidence seems to favor the ether pulse theory. Recent experiments by Laue and others seem to show the existence of diffraction effects when Röntgen rays pass through certain crystals. Whatever view we take of the gamma rays it seems well established that the Röntgen rays and the gamma rays are of the same nature. In the experiments referred to, a narrow beam of Röntgen rays was passed through a thin plate of a crystal, and the rays then fell on a photographic plate. In addition to the central spot produced by the rays directly transmitted, there were other spots arranged in more or less concentric circles around it. If we suppose, as we must, that in a crystal the molecules are regularly spaced, then a crystal plate will act as a diffraction grating. On the view that the Röntgen rays are ether pulses, these results receive a satisfactory explanation, while it would be difficult to explain them on any other view of the Röntgen rays. Accepting this view, estimates of the wave length of the Röntgen rays gave numbers in the neighborhood of 10^{-9} centimeters, about what was to be expected from the mode of their production.

LECTURE II

Introduction

It has been suggested to me that the meanings of some of the terms employed in the first lecture were rather uncertain to some of the audience, and the following chart has been prepared which may help to keep in mind the particular meanings of the terms employed throughout the lecture.

Cathode Particle **Beta Particle** **Corpuscle** **Electron**	A negatively charged particle, known only in motion, carrying the elementary electric charge: $e = 4.774 \times 10^{-10}$
Ion	A general term for a charged atom or molecule, or a cluster of atoms or molecules. May be charged either positively or negatively.
Alpha Particle	A positively charged atom of helium, carrying double the elementary charge, e.
Gamma Rays	Probably ether pulses produced by accelerations of the beta particles. Like Röntgen rays.

The four terms: cathode particle, beta particle, corpuscle, electron, all mean exactly the same thing. The distinction between them arises from the fact that the particles appear under different conditions. In the first place, the cathode particle is so called because it appears as if it were shot out from the cathode in a vacuum tube when an electric discharge is sent through. The beta particle is emitted by radioactive substances; the corpuscle and electron, which mean exactly the same, are general terms for both of these particles, and they are used when we wish to speak of them in general.

You will notice that I have not said anything on the chart in regard to the mass of these particles. This subject we shall have to come back to in the next lecture; but, roughly speaking, we can say that the mass of one of these particles is 1/2000 of the mass of the hydrogen atom; the hydrogen atom was, up to the discovery of these particles, the smallest known mass. Where I have used the word "atom," I mean exactly what chemists have always considered the atom to be; that is, the smallest mass which enters into chemical combinations.

Ion is a general term for any charged particle; frequently it is employed when the cathode or beta particle is meant. But usually by ion we mean a charged atom, or molecule, or a cluster of atoms or molecules which stick together around a central charge, which may be either positive or negative. Thus in the electrolysis of liquids, the current is carried by positive ions moving in one direction and negative ions moving in the opposite direction.

The alpha particle, about which we spoke last week, is a positively charged atom of helium; its mass is four times the mass of the hydrogen atom, and it carries a charge which is twice that of the cathode particle.

In regard to gamma rays, we saw last week that there is a good deal of evidence that they are electromagnetic disturbances, in every respect similar to light waves, except that their wave length is very much shorter than the wave length of any known light—something of the order of 1/1000 of the wave length of the shortest waves with which we are familiar.

The Disintegration Theory of Radioactivity

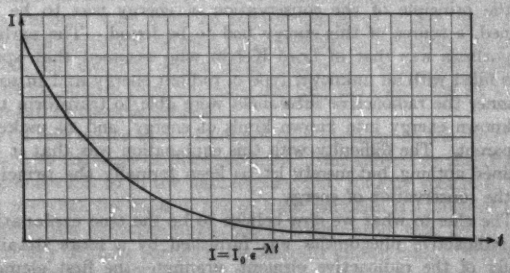
We have now given a brief account of the discovery of radioactive substances and of the chief characteristics of the radiations emitted by them. We proceed to consider an explanation of radioactive phenomena.

The most striking fact connected with the early study of radioactivity was the apparently continual emission of relatively large amounts of energy with no evident source of this energy. If the principle of the conservation of energy was to be retained, a source of this energy had to be found. The earliest hypothesis was that of Lord Kelvin, who assumed that space was filled with an unknown type of radiant energy and in some manner the radioactive substances were able to transform this unknown energy into known kinds of energy, and so make it apparent. The difficulty with this explanation was that it explained nothing, but merely let us keep formally the principle of the conservation of energy.

The clue to what we now believe to be the true explanation of radioactive phenomena was furnished by a more detailed study of the radioactive element, uranium—the first element which was discovered to be radioactive. It was found by Sir William Crookes that uranium could be separated into two constituents, one of which was inactive, and the other, much

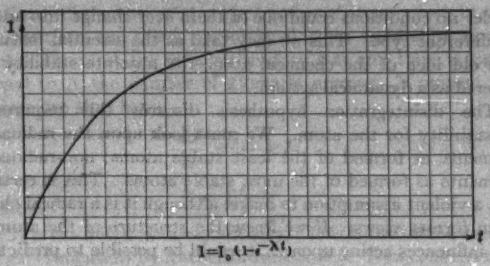
smaller in amount, was relatively intensely radioactive. His method of separation consisted simply in precipitating a solution of uranium nitrate by ammonium carbonate. The greater portion of the precipitate was redissolved by an excess of the reagent, but a residue, consisting chiefly of impurities in the uranium salt, was left undissolved. This residue carried with it the radioactive constituent of the uranium, and was given the name uranium X. The redissolved uranium was found to be inactive. But it is important to observe that tests of the radioactive property were made by the photographic and not the electrical method. Now it is the beta and gamma rays which produce, under usual conditions, the whole photographic effect. The alpha rays are so easily absorbed that the covering used to protect the plates from light also shields them from the alpha rays. The activity measured in these experiments may thus be called the beta-ray activity. On allowing the inactive uranium and the active uranium X to stand for a time it was found that the former recovered its initial activity after a few months, while the latter in the same time lost its activity. By making quantitative determinations of the radioactivity by the electrical method, using only the beta rays, Rutherford and Soddy determined the law of the decay of activity of the uranium X and the rise in activity of the uranium. Let I be the activity at any time, and Io the initial activity. The law of decay was found to be

$$I = I_0 \epsilon^{-\lambda t}$$



and the law of recovery

$$I = I_0 (1 - \epsilon^{-\lambda t})$$



where λ is a constant. The illustrations herewith show graphically the forms of the curves expressed by these two equations.

Results exactly analogous were obtained with thorium, from which a constituent thorium X was separated. In this case the decay of activity of the thorium X and the recovery of activity of thorium were much quicker than in the case of uranium. This means that the constant λ has a larger value for thorium than for uranium.

These results led Rutherford and Soddy to the disintegration hypothesis of radioactivity, which we shall now describe.

The old idea of the atom was that of an unchangeable mass, the smallest mass that could be thought of. There were as many different kinds of atoms as chemical elements. Of all the elements hydrogen has the lowest atomic weight and hence the hydrogen atom was supposed to be the smallest mass that could exist. It is true that there had been speculations in regard to the possibility of considering all atoms to be built up of various combinations of one substance, but there was no certain experimental foundation for such speculation and little, if any, progress was made in this direction. It was quite customary to look upon the atoms as hard elastic spheres of the various chemical elements. The study of the spectra of the various elements showed that no such simple view of the atom could be accepted; that the atom must be considered as a dynamical system in order to be capable of giving the very complicated system of spectral lines which most elements exhibit. But spectroscopy has not told us very much about the nature of the dynamical systems which we must take the atoms to be. Up to the time of the discovery of radioactivity, it was supposed that these dynamical systems forming the atoms were all stable systems—

under no conditions could one of them ever change into another of different type. This we may take as the essential feature of the old idea of the chemical atom—its absolute stability considered as a dynamical system.

The disintegration hypothesis discards this requirement of stability for the atom. We must look upon the radioactive elements as formed of the least stable atoms; non-radioactive elements as formed of the most stable atoms. This is certainly not a violent assumption to make, although it is a radical change from former views. If we knew the structure of the atom, all the influences acting upon it, it would be possible to predict just what each atom would do under any conditions. But we do not know this and so we have to make use of probability methods, just as in the kinetic theory of gases we make use of probability methods to find the mean velocity of the molecules.

Let us look upon the atoms as containing alpha and beta particles. We shall have more to say later as to the structure of the atom from this point of view. The atoms being unstable, in a given time a certain number of them will disintegrate, expelling one or more alpha or beta particles, or both. The atom thus changes into an atom of a different kind. Let us assume that the number of atoms which disintegrate in unit time is proportional to the whole number of atoms of its own kind present. If we start with N_0 atoms of a certain kind, the number N after a time t will be given by

$$\frac{dN}{dt} = -\lambda N$$

This expresses that the rate at which the atoms disintegrate is proportional to the whole number present at any time. We can integrate this equation at once, and get

$$N = N_0 \epsilon^{-\lambda t}$$

Thus, it is only after an infinite time has elapsed that all the atoms disintegrate. It will help our understanding of this theory to apply it to a definite case. Let us suppose that all the uranium X has been separated from a given amount of uranium by chemical means. We know that uranium X emits beta particles. Assume then that an atom of uranium X disintegrates into a non-radioactive atom and that the disintegration of each atom is accompanied by the expulsion of one beta particle. The number of beta particles emitted in a

given time will then be equal to the number of atoms which break up in that time, and this is proportional to the number of atoms present. Therefore the beta ray activity I at any time is proportional to N, the number of atoms of uranium X present at that time; we thus have

$$\frac{dI}{dt} = -\lambda I$$

$$I = I_0 \epsilon^{-\lambda t}$$

where I_0 is the initial beta ray activity. This is the law of decay found experimentally by Rutherford and Soddy. Now consider the uranium after the uranium X has been removed. It has no beta activity, but it is continually forming uranium X. Suppose then that an atom of uranium breaks up, expelling an alpha particle, and as a result changes into an atom of uranium X. Its beta ray activity depends upon the number of atoms of uranium X which have been formed. Let N, as before, be the number of atoms of uranium X present at any time t. The number of atoms of uranium is enormous; if the number that disintegrate during a few days is very small compared to the whole number, we can regard the rate of production of atoms of uranium X as constant. Call this q. Then

$$\frac{dN}{dt} = q - \lambda N$$

That is, the atoms of uranium X are produced at a rate q and disintegrate at a rate λN. So the net rate of increase is the difference between these two rates.

The integral of this equation is

$$N = \frac{1}{\lambda}\left(q - \epsilon^{-\lambda(t+c)}\right)$$

where c is the constant of integration

when

$$t = 0 \quad N = 0$$
$$t = \infty \quad N = N_0$$

So that

$$N = N_0 (1 - \epsilon^{-\lambda t})$$

Now since the beta ray activity of uranium is due to the uranium

X produced from it, the beta ray activity at a time t after the uranium X has been removed is

$$I = I_0 (1 - \epsilon^{-\lambda t})$$

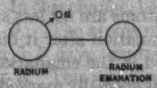
and this is the law Rutherford and Soddy found experimentally for the rise in activity of uranium after removal of uranium X.

After a long enough time has passed, five to six months in this case, the amount of uranium X becomes sensibly constant. In other words, there is radioactive equilibrium between the uranium and uranium X. Just as many atoms of uranium X are produced per second as are destroyed per second. It is not a true equilibrium because we have neglected the number of uranium atoms that disappear in comparison with the whole number. But the uranium atoms disintegrate at so slow a rate compared to the rate of disintegration of the uranium X atoms that the equilibrium between the two appears to be complete.

This hypothesis of the actual breaking down of the chemical atom and the resulting formation of a new atom did not meet with immediate acceptance. Chemists, in particular, were inclined to look upon the production of uranium X from uranium as a case of an ordinary chemical reaction. But this required the assumption that uranium itself was not an element, but a compound which slowly broke up spontaneously into its constituents, just as, under the influence of heat, most chemical compounds break up. But all known chemical reactions are subject to external conditions; temperature and pressure have a marked influence on their rate. The decay of uranium X, on the other hand appears to be absolutely independent of all external conditions. It goes on at the same rate at the temperature of liquid air as at the highest temperatures that may be obtained in an electric furnace. And the same holds true for all other radioactive processes. They appear to be inherent properties of the atoms themselves, and no means have yet been found of retarding or accelerating them.

We have now had two examples of radioactive disintegration—uranium and thorium. Let us now turn to radium and see how the disintegration hypothesis works out in this case. We have seen that radium has all the characteristics of a chemical element—a definite atomic weight, a definite spectrum, and distinct chemical properties so that it may be separated from other elements. Now in studying the radioactive properties of radium it was soon found that there were many irregularities in the

ionization produced by the rays from it. Air currents blowing over the uncovered radium, in particular, had a marked influence on the conductivity of the surrounding air. The ionization was much less from radium that had been freshly evaporated from solution than from the radium after it had stood for some days. Heating the radium produced a temporary diminution in its activity. It seemed as if a gaseous emanation, itself radioactive, was constantly forming in the radium and being occluded in it, so that heat and solution removed the store of this occluded gas. A simple way of studying this supposed gas was found in bubbling air through a solution of radium and collecting this air in a closed vessel. It was found that the conductivity of the air was enormously increased, that its conductivity gradually diminished, falling to half its initial value in about four days, but not according to a simple exponential law. It was found that objects immersed in it became themselves temporarily radioactive, particularly if they were negatively charged. This is the phenomenon known as induced or excited radioactivity. When radium was dissolved in water and air bubbled through the solution there was at first a very large amount of the emanation carried over. After a short time things reached a steady state. This may be explained by the disintegration hypothesis, if we assume that the radium atoms in disintegrating form atoms of emanation. This process goes on continuously and in the solid radium the emanation becomes occluded. In equilibrium there will be just as many atoms of the emanation formed in a second as disintegrate in a second—very little escapes from the solid radium. When the radium is in solution and air is bubbled through, the emanation is removed as fast as it is formed. The first stage in the disintegration of radium may then be represented:



We have spoken of this radium emanation as a gas and we must now examine the evidence for this assumption, and see what kind of a gas it is. If this assumption is correct it should have a definite spectrum, a definite density, and it should be possible to liquify it by increasing the pressure or lowering the temperature, or both. First, as to its spectrum. The emanation from a large quantity of radium was collected, freed from impurities and introduced into a spectrum tube. A wholly new set of

spectral lines, unlike the lines from any known substance, was found. In the course of a few days this spectrum gradually weakened and disappeared, the spectrum of helium finally taking its place. This is of course exactly what we should expect if the emanation disintegrates with the expulsion of alpha particles, for the alpha particles are charged atoms of helium.

Rutherford succeeded in liquifying the emanation at a temperature of -65 deg. cent. at atmospheric pressure. The vapor pressure of the liquid emanation has been determined for a wide range of temperature. Thus, in this respect, it behaves as an ordinary gas.

The determination of the density of the radium emanation was accomplished by Sir William Ramsay. It was a problem requiring extraordinary experimental skill for its solution. The method consisted in actually weighing a known volume of the emanation. When we consider that the weight of the emanation was of the order of $\frac{1}{1000}$ of a milligram it will readily be seen that a very accurate determination was impossible. The density was found to be 111.5 times that of hydrogen, and assuming that the emanation is a monatomic gas, this makes the atomic weight 223. The atomic weight of radium is 226; and if, then, the radium atom emits in disintegrating a single particle, whose weight is 4—the atomic weight of helium—this should leave for the atomic weight of emanation, into which the radium disintegrates, the value 222. This is in surprisingly good agreement with the number found when we remember the extremely small amount of the emanation available.

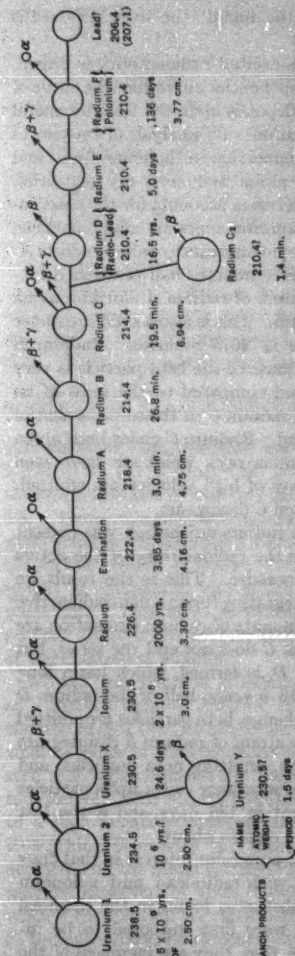
We are thus justified in looking upon the radium emanation as a gaseous element differing in no respect from an ordinary element except that its atoms are far less stable. Let us now see what becomes of the emanation after it disintegrates. We have seen that solids immersed in the emanation become temporarily radioactive. This effect is specially marked if conductors charged to a high negative potential are immersed in the emanation. Everything is exactly the same as if a solid substance were deposited on the metal surface. For example, this active deposit may be dissolved in acids, leaving the metal non-radioactive; while if the solution is evaporated to dryness the residue is found to be radioactive, its radioactivity diminishing in the same way it would have if left on the metal. The active deposit may also

be removed by sandpapering the metal; the dust removed is then radioactive.

When the decay curve of this excited radioactivity is drawn, it is found not to be a simple exponential curve like the curve of decay of uranium X. Its form depends upon the time the metal has been immersed in the emanation. By analysis of the curves obtained for different times of immersion in the emanation and by measuring separately the alpha and beta ray activities, it is found that the following succession accounts for the observations. The atom of radium emanation emits an alpha particle, and becomes then an atom of a solid substance, called radium A. Radium A has a short life; in three minutes half of it has disappeared. In disintegrating, the atom of radium A emits an alpha particle and changes into radium B. This is also a solid substance disintegrating to half its value in 26.5 minutes. Radium B emits only beta particles. The mass of the beta particle is very small so that it can be neglected compared to the mass of an atom; thus the atomic weight of radium C is the same as that of radium B from which it is formed. Radium C emits both alpha and beta particles; and also gamma rays, which we have seen are to be expected when beta rays of high velocity are emitted. In 19.5 minutes half of the radium C disappears.

If only a small amount of the radium emanation was present to begin with, after a few hours the radioactivity of the active deposit becomes too small to measure. This is the result we should have if radium C on disintegrating forms a non-radioactive substance. If, however, large amounts of radium emanation are employed it is found that radium C does not end the series, but that another substance, radium D, is formed, which has a long life compared to radium C. In 16.5 years, half of the radium D changes into radium E. In this change, beta particles are emitted by the atoms of radium D. The atoms of radium E disintegrate to half their number in 5.5 days, emitting beta particles, and forming atoms of radium F. This substance emits alpha particles only, decaying to half its amount in 136 days, and is the last member of the series that we are certain about.

Radium D and radium F are of particular interest in that they have been found to be identical with radio-lead and polonium respectively—two radioactive substances found in the chemical analysis of pitchblende, which were first supposed to be independent substances. We see that they are members of the family which is formed by the disintegration of radium.



You will notice that for the last member of this family I have put down lead, with an interrogation point. The evidence for this is not conclusive, but there is enough to make it seem probable. In the first place, assuming that every time an alpha particle is emitted the weight of the atom is reduced by 4, the atomic weight of helium, the last member of the series should have an atomic weight equal to that of radium, less four times the number of alpha particles emitted in the complete disintegration. Looking at the diagram we see that there are five changes which are accompanied by the emission of an alpha particle. So the atomic weight of the last member of the series should be

$$226.4 - 4 \times 5 = 206.4$$

The element that has an atomic weight nearest this number is lead, whose atomic weight is 207. The discrepancy between these two numbers may possibly be accounted for in this way. There is some evidence that the atoms of radium *C* break down in two different ways. Some of them yield radium *D* and the others yield a substance called radium C_2. On the diagram this is called a branch product. If radium C_2 with a probable atomic weight of 210.4 disintegrates without emitting any alpha rays the final product will have the same atomic weight. As the amount of

radium C that forms the branch product is small compared to the amount that forms radium D, the mean atomic weight of the two final products would be somewhat greater than 206.4 and might therefore be assumed to be equal to the atomic weight of lead. This view requires us to regard what we call lead as a mixture of atoms of two different kinds, of chemical properties so similar that no way has ever been found of separating them. There is nothing inherently improbable in this view and it is suggested as one way of identifying the final member of the radium family as lead. Indirect evidence that this is so is found in the fact that in many minerals there is a definite relation between the amounts of radium and lead present. This could hardly be explained in any way than that lead is formed from radium.

Let us now examine the other end of the series. It has been well established that in uranium minerals there is a fixed ratio between the radium and uranium present. It is found that for every gram of uranium there is an amount of radium equal to 3.4×10^{-7} grams. A very few minerals show exceptions to this ratio; but these exceptions are satisfactorily accounted for by decompositions or chemical replacements for which there is other evidence. As uranium has the highest atomic weight of all the known elements we naturally take it as the parent element in the whole series.

We saw that the discovery leading to the disintegration hypothesis was that from uranium a substance, uranium X, continually produced by the uranium, could be separated by chemical means. There is evidence, however, which there is not time to give here, that uranium does not disintegrate directly into uranium X, but into an intermediate substance, uranium 2, the disintegration of each atom being accompanied by the expulsion of an alpha particle. We know of no method by which uranium 1 and uranium 2 can be separated. We may look upon what we call uranium as in reality a mixture of two substances, uranium 1 with atomic weight 238.5 and uranium 2, with atomic weight 234.5; the latter is present in so small a proportion as not to affect the mean atomic weight, which is that of uranium as we know it (238.5). Between uranium X and radium there is one member, ionium, discovered by Boltwood. The atoms of ionium disintegrate, with the expulsion of an alpha particle, into atoms of radium.

We must now see how it is possible to determine the rate of decay of the various members of the series. For those that decay

rapidly—say to half their initial value in a few months or less—the rate of decay may be determined by analysing the curves obtained by measuring their radioactivity over a sufficiently long period. But this method obviously cannot be employed for those substances which decay very slowly. The period of radium may be determined in the following way. I showed in the previous lecture how the whole number of alpha particles emitted in a second by a radioactive substance can be counted. If we assume that each radium atom on disintegrating emits a single alpha particle, then the number of atoms of radium that break down in a second is equal to the number of alpha particles emitted by it in a second. The ratio of the number that break down per second to the whole number present is the constant λ in the equation

$$N = N_0 \epsilon^{-\lambda t}$$

Now Rutherford has found that the whole number of alpha particles emitted in a second by one gram of radium is 3.4×10^{10}. We now must find the number of atoms of radium in one gram. A cubic centimeter of hydrogen has a mass of 9×10^{-5} grams. If there are n molecules in a cubic centimeter of any gas, there are $2n$ atoms of hydrogen in a cubic centimeter. So that in one gram of hydrogen there are $\frac{2n}{9 \times 10^{-5}}$ atoms. In one gram of radium there will accordingly be

$$\frac{2n}{9 \times 10^{-5} \times 226.4} \text{ atoms}$$

Taking $n = 6.12 \times 10^{19}$ we find the number of atoms in one gram of radium to be

$$3 \times 10^{21}$$

Therefore

$$\lambda = \frac{3.4 \times 10^{10}}{3 \times 10^{21}} = 1.1 \times 10^{-11}$$

Now, remembering that $N = N_0 \epsilon^{-\lambda t}$, and putting $N = \frac{1}{2} N_0$ we find

$$\epsilon^{-\lambda T} = \frac{1}{2}$$

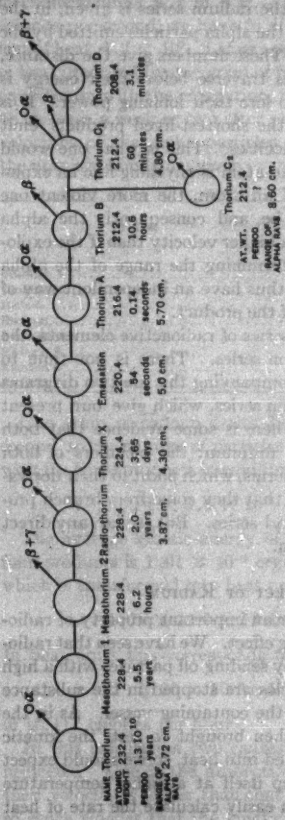
where T is the time for the substances to be half transformed.

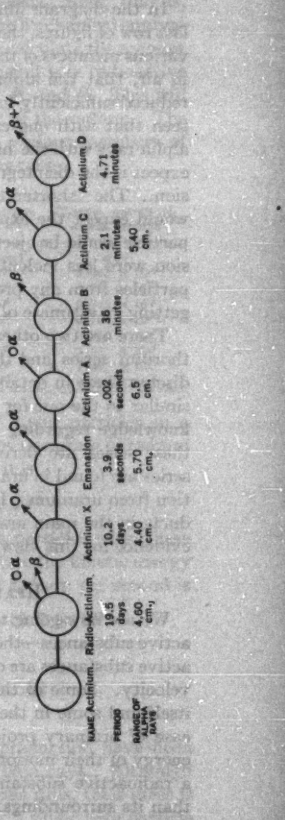
Therefore

$$T = \frac{\log 2}{\lambda} = \frac{0.693}{\lambda}$$

For radium, therefore, $T = 6.3 \times 10^{10}$ seconds or 2000 years.

This same method may be applied to any substances which emit alpha rays that can be counted.





Since the uranium atom emits altogether three alpha particles in changing to radium, the atomic weight of the latter should be

$$238.5 - 3 \times 4 = 226.5.$$

This is in excellent agreement with the value found for it by Madame Curie.

In the diagram illustrating the radium series is given, in the last row of figures, the range of the alpha particles emitted by the various members of the series. These numbers give the distance, in air, that the alpha particles traverse before their energy is reduced sufficiently for them to lose their ionizing power. It is seen that with one exception the shortest-lived products emit alpha rays with the highest velocities. This is what one would expect if the disintegration of an atom is anything like an explosion. The shorter the life of an atom, the more violent one would expect the explosion to be, and consequently the alpha particle would be ejected with a higher velocity than if the explosion were less violent. By determining the range of the alpha particles from any product we thus have an independent way of getting an estimate of the life of the product.

There are two other known series of radioactive elements, the thorium series and the actinium series. There is not time to discuss these in detail, but accompanying this are two diagrams similar to the one for the radium series, which give our present knowledge regarding them. There is some evidence that both these series are derived from uranium; the members of both series are found in uranium minerals, which point to their derivation from uranium. It may be that they come from branch products in the main uranium—lead series. But, so far, any direct evidence for this view is lacking.

Heating Effect of Radium

We are now going to consider an important property of radioactive substances—their heating effect. We have seen that radioactive substances are continually sending off particles with a high velocity. Some of these particles are stopped in the substance itself and some in the walls of the containing vessel. As in the case of ordinary projectiles, when brought to rest, the kinetic energy of their motion is changed into heat, so we should expect a radioactive substance to keep itself at a higher temperature than its surroundings. We can easily calculate the rate of heat

production in any radioactive substance as soon as we know the number, mass, and velocity of the particles emitted by it in a given time. For each particle of mass m and velocity v has an amount of kinetic energy equal to $\frac{1}{2} m v^2$. If n particles are emitted in a second the whole kinetic energy is $\frac{1}{2} m n v^2$, and if all these particles are brought to rest the heat produced in mechanical units is $\frac{1}{2} m n v^2$. To get thermal units, that is, calories per second, we have to divide by the mechanical equivalent of heat, 4.2×10^7. Let us apply this to calculate the amount of heat produced by one gram of radium when it is in radioactive equilibrium with the emanation, radium A, B, and C. This will be the case a week or two after preparation of the radium. The velocities of the alpha particles from the various members of the uranium family are given in the following table.

Product	Velocity of alpha particle	Kinetic energy of alpha particle
	cm. per second	ergs
Uranium 1	1.45×10^9	0.645×10^{-5}
Uranium 2	1.53×10^9	0.72×10^{-5}
Ionium	1.56×10^9	0.746×10^{-5}
Radium	1.61×10^9	0.794×10^{-5}
Emanation	1.73×10^9	0.915×10^{-5}
Radium A	1.82×10^9	1.01×10^{-5}
Radium C	2.06×10^9	1.31×10^{-5}
Radium F	1.68×10^9	0.866×10^{-5}

One gram of radium emits 3.4×10^{10} alpha particles in a second; so the number of particles emitted by one gram of radium with the three products in equilibrium with it is

$$4 \times 3.4 \times 10^{10} = 13.6 \times 10^{10}$$

The average kinetic energy of the alpha particles from these four products is 1.01×10^{-5} ergs. Therefore the kinetic energy which is transformed into heat per gram of radium per second is

$$1.01 \times 10^{-5} \times 13.6 \times 10^{10} = 13.7 \times 10^5$$

In heat units this corresponds to

$$3.26 \times 10^{-2} \text{ calories per second}$$

or to 117 calories per hour.

In this calculation two causes of heat production have been neglected. One is the absorption of the beta rays. Although their velocity is higher than that of the alpha rays, their mass is so much smaller that the kinetic energy of a single beta particle

is only a small fraction of the kinetic energy of a single alpha particle. Then the kinetic energy of the recoil of the atom, resulting from the expulsion of the alpha particle, has been neglected. This may easily be calculated; for the momentum of the atom is equal in magnitude and opposite in sign to the momentum of the particle. The latter is known, as is the mass of the atom, and so the velocity of the atom is

$$mv/M$$

where m is the mass of the alpha particle (4) and M that of the atom after the alpha particle has been expelled; v is the velocity of the alpha particle. The total heating effect resulting from the recoil of the atoms is less than one per cent of the effect we have calculated. As a result, we find that the heating effect of one gram of radium a few days after its preparation is

118 calories per hour.

Now this is something that can be measured, by placing a known mass of radium in a calorimeter and observing the increase in temperature. Measurements of this kind give results very near the calculated value. In particular, one measurement of Rutherford gave as the heating effect of the radium emanation from one gram of radium, 94.5 calories per hour. The value calculated by the same method as that employed for radium is 94 calories per hour. These results therefore confirm the hypothesis that a single alpha particle is emitted from an atom when it disintegrates.

Another confirmation of the disintegration hypothesis is found in the agreement between the calculated and the measured rate of production of helium. Assuming each alpha particle to be an atom of helium, the number of atoms of helium formed in one second in one gram of radium in equilibrium with the emanation, radium A, B, and C, is

$$4 \times 3.4 \times 10^{10} = 13.6 \times 10^{10}$$

In one cubic centimeter of helium at a pressure of 760 mm. of mercury and at 0 deg. cent. there are

$$2.78 \times 10^{19} \text{ atoms}$$

Therefore in one year there should be produced 154 cubic millimeters of helium. Direct experiment, by Sir James Dewar, gave 169 cubic millimeters a year from one gram of radium. When one considers the difficulty of measuring the extremely small volumes

of helium produced from a small amount of radium in a comparatively short time, the agreement between these numbers is surprisingly good.

Radioactivity and the Age of the Earth

The heating effect of radium and the other radioactive substances has an important bearing upon the problem of the age of the earth. You know that there has been a long-standing controversy between physicists and geologists about this problem. There are two principal methods of getting an estimate of the earth's age by physical reasoning. One method is to calculate the time required for the sun to reach its present size by contraction from an infinite sphere, radiating the heat thus produced at the rate determined by measuring the heat received in unit time on unit surface of the earth. The other method is to calculate the time it would take the earth to reach its present temperature, or rather its present rate of increase in temperature (about 1 deg. cent. in 100 feet) downwards from the surface. These methods give as the limiting age of the earth something between twenty and sixty million years. Now this is altogether too short a time to satisfy geologists, who base their reasoning partly on the fossils found in the different geological strata, and partly on the salt content of the oceans, assuming this to have been brought there from the land.

Lord Kelvin was careful to state that his low estimate of the age of the earth depended on no other source of heat energy being found. We now know that there is another source of heat energy, and that is the heating effect of radioactive substances. Nearly all rocks found on and near the surface of the earth are radioactive. The amount of radium contained in the common rocks in different parts of the world varies between wide limits. Some have a radium content as low as 1.2×10^{-13} grams of radium per gram of rock. But on the average, the surface rocks have a radium content of about 2×10^{-12} grams of radium per gram of rock; they also contain about 6×10^{-6} grams of uranium and 1.2×10^{-5} grams of thorium per gram of rock. If it is assumed that these proportions hold throughout the earth, there would result, from the heating effect of radioactive substances alone, more than ten times the amount of heat that is necessary to account for the present temperature gradient of the earth. So it is probable that the interior of the earth contains far less radium than is indicated by the surface. As a result of the discoveries

in radioactivity, physicists will now allow the geologists all the time they require for the earth to have reached its present state.

There is another interesting application of the study of radioactivity to geology. If the amount of helium in a mineral be measured, and it be assumed that all the helium is a result of radioactive disintegration, a minimum estimate of the age of the mineral can be determined. Such estimates lead to times varying from 200 million years to 1600 million years.

There is another subject that should be spoken of in connection with the disintegration hypothesis we have been describing. That is the question of the possibility of reversing any of these radioactive changes, and of bringing about disintegration in atoms which under ordinary circumstances are stable. The disintegrations we have described take place of themselves. External conditions appear to have no effect upon them. It has not been found possible in any way whatever to change the rate at which they take place. For example, radium emanation may be passed through a white-hot platinum tube; it still decays at the same rate. It may be condensed to a solid; the solid emanation decays at the same rate as the gaseous emanation. Now the question is, is it possible to cause the atoms of substances not known to be radioactive to disintegrate? A few years ago Sir William Ramsay announced that he had succeeded in producing lithium in a solution of copper containing a large amount of radium emanation. The reasoning which led him to make such an experiment was this. Radium emanation, in its disintegration, liberates an enormous amount of energy compared to the energy involved in any ordinary chemical change. The amount of energy liberated by one cubic centimeter of radium emanation is about ten million times the amount of energy liberated when a cubic centimeter of hydrogen is burned. And the latter is the chemical change which yields the greatest amount of energy of any ordinary chemical process. If, now, this energy liberated in the disintegration of the emanation can be brought to bear upon the atoms of ordinary elements, there might be a possiblity of breaking them up. A favorable condition for making this experiment is to have the emanation in solution with another substance, and Sir William Ramsay thought that in this way he had succeeded in breaking up copper atoms, with atoms of lithium as one of the products. The experiment has been repeated by others, but no confirmation of it has thus far been obtained. So we cannot say that the possibility of breaking up an atom of non-radioactive matter has been proved.

Many of you have probably seen accounts during the last few weeks of experiments by Collie and Patterson, in England, on the actual building up of chemical elements. Their experiments did not make use of the energy liberated in the disintegration of a radioactive substance, but they employed the energy of an electrical discharge through vacuum tubes. In brief, their experiments consisted in passing electric discharges through vacuum tubes, breaking up the glass, and heating it to drive off any occluded gas. This gas was then examined spectroscopically, and it was found to contain small amounts of helium and neon. They ascribed the presence of these gases to an actual synthesis resulting from the electric current. While it is impossible to say definitely that their conclusion is not true, there are too many other possible ways of accounting for the presence of these gases to give us much confidence in their experiments as proving the synthesis of matter. Inasmuch as the disintegration of a single atom of a radioactive substance involves the liberation of a relatively enormous amount of energy, one would expect that an equivalent amount of energy would be required to build up an atom. So we must feel very sceptical about accepting as true the possibility of the synthesis of matter. The whole problem is a fascinating one, but we cannot say that any certain progress has been made in its solution.

So far, of the previously known elements, only two of them, uranium and thorium, have been found to have marked radioactive properties. It is an interesting question whether the other elements also are radioactive. We should rather expect this to be the case. If we regard the atoms of the various chemical elements as dynamical systems, we should expect them to exhibit various degrees of stability; the elements that we call radioactive are formed of the least stable atoms; and the elements that we call non-radioactive are so only because their atoms are so stable that too few of them disintegrate in a given time to produce radioactive effects. It is known that other properties are shared by all elements in varying degrees. Take, for example, the magnetic property. All elements show a magnetic quality, but it is only a few of them, notably iron, nickel, and cobalt, that have this property to any marked extent.

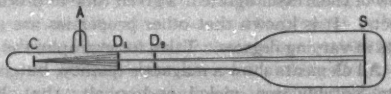
There is a good deal of evidence that the metals rubidium, potassium, and sodium are radioactive, although much less so than uranium and thorium. The wide distribution of radium, found, as it is, in minute quantity in nearly all minerals, gives

rise to the suspicion that the observed radioactivity of ordinary materials may result from the presence of a trace of radium. But in the case of the three metals mentioned, the fact that their observed activity seems to be independent of their source or method of preparation, leads to the view that they are themselves really radioactive substances. And, besides, the rays emitted by them have a character distinct from those emitted by any of the other known radioactive substances. Great care is needed in making experiments to determine the presence of minute traces of radioactivity; for laboratories in which radium emanation has been allowed to escape soon become contaminated by the active deposit that forms on the walls and on all solid objects, so that there is always the possibility of getting spurious effects.

In this lecture I have attempted to show that our old idea of the atoms of the elements as necessarily permanent, must be given up. Instead, we must look upon the atoms of the radioactive elements as unstable dynamical systems. And, probably, the atoms of all elements must be thought of in the same way. Those which appear to be non-radioactive may be thought of as formed of relatively stable atoms, disintegrating at too slow a rate to make it possible, by any means we now know, to detect radioactive effects from them. This view involves no violation of the principle of the conservation of energy. The energy emitted by the radioactive substances in the three kinds of rays is drawn from the internal supply of energy of the atoms.

LECTURE III

The purpose of this lecture was to illustrate by experiment some of the phenomena described in the previous lectures, and to give a little fuller account of some of the subjects touched upon. The first experiments shown had for their object the illustration of the chief characteristics of the cathode rays. By means

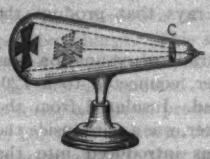


of an induction coil an electric discharge was maintained in a tube of the form illustrated herewith. C is the cathode and A the anode. D_1, D_2 are two diaphragms with small holes which serve to limit the beam of cathode rays, so that they produce a spot of light on the phosphorescent screen, S. By bringing

a magnet near the tube the spot of light was made to move over the phosphorescent screen. The direction in which the spot moved was shown to be what one would expect if the cathode stream is a flow of negatively charged particles, travelling from left to right. For example, when the north pole of the magnet was brought near to, and above the tube, the spot moved forwards; when the north pole of the magnet was brought in front of the tube the spot moved down. In its undeflected position the spot of light was a small circular area. In its deflected position it had broadened out to a band. This was accounted for by the differences in the velocities of the particles. Recalling the expression for the deflection of a charged particle in a magnetic field

$$H\frac{e}{m} = \frac{v}{\rho}$$

it is seen that the faster moving particles are less deflected than the slow moving particles. As the cathode particles are shot out with all velocities within a certain range, the result is to broaden the spot of light into a band when a magnetic field is applied.



A tube of different form, as in the accompanying illustration, was next shown, which contained an obstacle, in the form of a cross which could be raised or lowered. When it was down, the cathode particles, striking the glass, produced a greenish-yellow phosphorescence. It was the similarity between this light, and the light emitted by certain uranium compounds after exposure to sunlight, that led Becquerel to make the first discovery of radioactive phenomena.

When the cross was raised its shadow was seen as a dark region on the glass, since the obstacle prevented the particles from striking the glass.

Next were shown experiments illustrating the conductivity of air traversed by the rays from radioactive substances. The electric currents passing through the air were measured by the rate of discharge of a parallel plate condenser when a radioactive substance was spread on the lower plate. And this was given by the rate of fall of potential of the insulated plate, when the other plate was charged to a definite potential. The current is given by

$$i = C\frac{dV}{dt}$$

where C is the capacity of the condenser, together with that of the electrometer and the connecting wire. In the experiment this capacity was about 100 in electrostatic units. The electrometer had a sensitiveness such that a potential difference of one volt produced a deflection of about 1000 divisions on the scale. Thus when the electrometer needle moved ten divisions a second, the current flowing through the air was roughly 10^{-13} amperes. It is feasible to measure, by this method, currents as low as 10^{-16} amperes.

Some uranium oxide was spread on the lower plate of the condenser and the motion of the spot of light over the scale determined. Then some of the powdered mineral pitchblende was tested and the spot of light moved about four times as fast, indicating that the radioactivity of pitchblende is about four times that of uranium oxide. A tube of radium, lent by Dr. Kunz, was then placed in the condenser and the spot of light rapidly moved off the scale. In this case the conductivity produced was due to the beta and gamma rays, since the alpha rays were absorbed in the containing tube. With an uncovered radioactive substance it is the alpha rays that produce the greater part of the conductivity.

The conductivity of air containing radium emanation was then shown. For this, a brass cylinder, connected to a 120-volt direct-current circuit, was employed. Insulated from the cylinder, and connected to the electrometer, was a wire inside the cylinder. When radium emanation was introduced into the cylinder, by bubbling air through a solution of radium, and blowing it into the cylinder, a very large increase in the rate of motion of the electrometer needle was seen.

Finally the phenomenon of excited or induced radioactivity was illustrated. A wire, charged to a negative potential, was suspended in a cylinder containing radium emanation, for two or three minutes, and then taken out, and its activity measured in the condenser used in the first experiments on radioactivity. It was found that the wire had a definite activity to begin with, and observations a few minutes apart showed that its radioactivity gradually decayed.

There are some points in connection with the previous lectures about which more should be said. We have seen that a wire placed in radium emanation becomes radioactive itself, and this was explained as caused by the deposition on the wire of solid particles of radium A resulting from the expulsion of an

alpha particle from the atom of radium emanation. As the alpha particle is positively charged, we should expect the atoms of radium *A* to be negatively charged, and therefore to tend to concentrate on positively charged surfaces. Exactly the opposite is found to be the case. More of the active deposit forms on a negatively charged surface than on a positively charged surface, other conditions being the same. This difficulty has been cleared up by the discovery of what are called "delta" rays. These are negatively charged particles, which travel at too low a velocity to produce any ionizing effects, and which always accompany the emission of alpha particles. They were found in this way. Suppose a radioactive substance, like polonium, which emits alpha rays, but no beta rays, is placed opposite a metal plate, in a very high vacuum, so that the alpha particles will strike the metal plate without, on the way, hitting any air molecules to ionize. We should expect the metal plate to receive a positive charge—the product of the charge of the alpha particle by the number of particles that strike it. It is found, however, when the experiment is made, that the metal plate does not get positively charged. However, by applying a weak magnetic field in a direction parallel to the plate, the latter receives a positive charge. This is exactly the effect that would be produced if, with the positively charged alpha particles, negative particles are emitted. These delta rays travel with so low a velocity as not to produce any appreciable ionization; they are of the same nature as the beta particles except that their velocity is so small that they are very readily deflected by a magnetic field. If, then, when an atom of radium emanation disintegrates, with the expulsion of an alpha particle, it also expels a sufficient number of delta particles, the atom of radium *A* will be positively charged, and will therefore travel to the negative electrode.

The law of decay that has been found experimentally for a single radioactive substance,

$$I = I_0 \epsilon^{-\lambda t}$$

we have seen, can be deduced from the assumption that the number of atoms that disintegrate in a second is proportional to the whole number present. This may be looked at from another point of view. We may regard each of the atoms of a radioactive substance as equally likely to disintegrate. Not knowing the circumstances that cause an atom to disintegrate, and not being able to follow each atom throughout its whole life, we have to make use of the method of the calculus of proba-

bilities in its simplest form. The calculus of probabilities is, perhaps, the most powerful mathematical method we have for dealing with problems involving atoms or molecules. Its justification lies in its success in accounting for many phenomena. The atoms all being equally likely to disintegrate, the number that do so will be proportional to the whole number. We might look upon the atoms as kernels of corn; the disintegration of an atom as the popping of a kernel. The illustration is not perfect, because as the corn gets hotter the rate of popping increases. But there is a stage which lasts for some minutes, at which the popping occurs fairly regularly. Now it is obvious that with only a few kernels to begin with, there would be no regularity in the popping. One kernel would pop, then several seconds might elapse and a number of them would pop almost simultaneously, and then there might be a fairly long interval before another one popped. But with a very large number of kernels to begin with, the irregularities are smoothed out. In the steady state referred to, as many kernels pop in one second as in the succeeding one. Thus with a very large number of kernels, probability becomes certainty. So it is in the familiar illustration of chance as applied to drawing a certain card from a pack. The probability of drawing a certain card at one trial is the ratio 1/52. But every one knows that it rarely happens that out of 52 trials the given card is drawn once and only once. It may not be drawn at all, or it may be drawn many times. If, however, there be a very large number of observers, each with a pack of cards, all drawing together, the likelihood that one out of every 52 will draw the given card becomes very much increased; so that with an enormous number of observers, this probability becomes a certainty.

The method, described in the first lecture, of counting the number of alpha particles emitted by a radioactive substance, furnishes a good illustration of this point. If the opening, through which the particles enter the ionization chamber, is made very small, then the ratio of the whole number that enter to the whole number emitted, is very small. The result is that the particles do not enter at equal time intervals. One particle enters, some seconds may elapse, and then two or more particles may enter almost simultaneously. So, to get definite results observations must be taken during a long time; the longer the time during which observations are made, the more accurate are the results in giving the rate at which the particles enter.

Now even in what we call infinitesimal amounts of matter there are enormous numbers of atoms. Therefore the probability that a certain fraction of them will disintegrate in a given time becomes a certainty that they will do so.

The particular fraction is the quantity λ which is characteristic of each substance. For a substance which is not at all radioactive λ is zero. The greater λ the more radioactive the substance. We have seen that the time required for a substance to disintegrate to one-half its initial value is related to λ by the equation

$$T = \frac{0.693}{\lambda}$$

Another interpretation of this important quantity is that its reciprocal tells us the average life of an atom. For if we start with N_0 atoms, the number at any time, t, will be

$$N = N_0 \epsilon^{-\lambda t}$$

The average life of an atom is therefore

$$\frac{1}{N_0} \int_0^\infty N_0 \epsilon^{-\lambda t} dt = \frac{1}{\lambda}$$

The meaning of "radioactive equilibrium" may require a little more explanation. Let us consider what is meant by saying that in a mineral containing uranium, equilibrium exists between the uranium and all its products. By referring to the chart which gives a representation of the whole known series of disintegrations, we see that uranium has a far longer life than any of its radioactive products. If we began with uranium and could remove all of its products from it, the latter would begin to form at once, and after a long enough time had elapsed, as many atoms of one of the products would form, in a given time, as disintegrated in the same time. Uranium would then be in equilibrium with its products. Since the uranium itself is breaking down, and, so far as we know, is not being continually formed from any element of higher atomic weight, the uranium itself would not be in equilibrium.

If there are two successive products, 1 and 2, so that 2 is

formed by the disintegration of 1, the rate of increase of atoms of 2 will be given by

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2$$

for $\lambda_1 N_1$ is the number of atoms of 1 that break down a second; that is, the rate of formation of atoms of 2; $\lambda_2 N_2$ is the rate of disintegration of atoms of 2. So the difference gives the net rate of increase of 2. If there is radioactive equilibrium between 1 and 2, $dN_2/dt = 0$; that is, the number of atoms of 2 that form from 1 per second must be equal to the number of atoms of 2 that disappear per second. So that

$$\lambda_1 N_1 = \lambda_2 N_2$$

or

$$N_2 = \frac{\lambda_1}{\lambda_2} N_1$$

If A_1 and A_2 are the atomic weights of the two products, the mass of 1, M_1, in equilibrium with a mass M_2 of 2 will be

$$M_2 = \frac{\lambda_1}{\lambda_2} \frac{A_2}{A_1} M_1$$

or if T_1 and T_2 are the times for 1 and 2 to be half transformed, we can write this

$$M_2 = \frac{T_2}{T_1} \frac{A_2}{A_1} M_1$$

By the use of this equation we can find the amount of any product in equilibrium with its parent. Suppose we have a mineral containing one gram of radium. The amounts of the various products in equilibrium with this will then be given by the successive applications of this equation. In this way we can calculate the following table:

Name	A	T	M grams
Radium	226.4	2000 yr.	1
Emanation	222.4	3.85 days	$5.2\ 10^{-6}$
Radium A	218.4	3 min.	$2.8\ 10^{-9}$
Radium B	214.4	26.8 min.	$2.4\ 10^{-8}$
Radium C	214.4	19.5 min.	$1.8\ 10^{-8}$
Radium D	210.4	16.5 yr.	$7.9\ 10^{-3}$
Radium E	210.4	5 days	$6.5\ 10^{-6}$
Radium F	210.4	136 days	$1.8\ 10^{-4}$

We see that in a mineral containing one gram of radium we must expect to find 1.8×10^{-4} grams of polonium (radium F). The amount of the latter which can be obtained is therefore extremely small.

It is found that in a mineral containing one gram of uranium there is an amount of radium equal to 3.4×10^{-7} grams. So, in order to find the amount of any of the products of radium in equilibrium with one gram of uranium, we need only multiply the numbers in the last column of the above table by 3.4×10^{-7}.

We must believe that each member of the uranium series, and also each member of the thorium and actinium series, is a definite chemical element, with definite chemical properties and a definite spectrum. The reason why the properties of so few of these elements are known is now seen to be the result of the very minute amounts of them that are available. In the uranium series, we have fairly complete knowledge of the chemical properties and the spectra of uranium, radium, and the emanation. There is some evidence, also, of a definite spectrum belonging to radium F (polonium). Many of the chemical properties of the other members of this series are known, but this knowledge is by no means complete.

A great deal of interest has been aroused in the medical applications of radium. So far as we know, there is no other practical use for it. The rays emitted by radium produce burns which are similar to those produced by ultra-violet light and the Röntgen rays, and it is to be expected that they should possess a therapeutic value. I am not able to speak with any authority on this subject, but it is a fact that a good deal of work is being done—particularly in England and on the continent—along these lines, and announcements of success in the application of radium and the radium emanation are frequently made. Progress in this direction is retarded by the small amount of radium which is available. The principal source of radium is the mineral pitchblende, and the chief known deposits of this mineral are owned by the Austrian government, which also controls the manufacture of radium from it.

In conclusion I am going to give an approximate calculation of the amount of energy set free when one gram of uranium is transformed into the last member of the series, which we may take to be lead. In this transformation eight alpha particles are emitted, with an average velocity of

$$v = 1.68 \times 10^9 \text{ cm. per second}$$

The mass of an alpha particle is four times the mass of an atom of hydrogen, or $m = 4 \times 1.7 \times 10^{-24}$.

Thus the average kinetic energy of the alpha particles emitted by uranium is $\frac{1}{2} m v^2$, or

$$9.6 \times 10^{-6} \text{ ergs}$$

and the kinetic energy of the eight alpha particles is therefore

$$7.7 \times 10^{-5} \text{ ergs.}$$

This is the energy set free when one atom of uranium breaks down into lead. In one gram of uranium there are

$$\frac{1}{238.5 \times 1.7 \times 10^{-24}} = 2.5 \times 10^{21} \text{ atoms.}$$

Therefore the energy set free when one gram of uranium turns to lead is $7.7 \times 10^{-5} \times 2.5 \times 10^{21} = 1.9 \times 10^{17}$ ergs.

Now suppose it were possible enormously to increase the rate at which this change takes place. Instead of millions of years, suppose it took place in one second. The rate at which work would be done is then

$$\frac{1.9 \times 10^{17}}{7.46 \times 10^{9}} = 2.5 \times 10^{7} \text{ horse-power.}$$

Uranium thus has an enormous store of energy contained in its atoms. We must believe that all the elements contain equivalent amounts of energy in their atoms. But no means is known of drawing upon this supply of energy, nor even of hastening its liberation from those elements which do disintegrate spontaneously.

It is the province of science to discover the laws of nature; the province of engineering is to apply them. And therefore we must leave to the engineers the problem of making use of this enormous store of energy concealed in the atoms of all matter.

LECTURE IV

I am going to speak of a discovery connected with radioactivity which is of very far reaching importance. It has to do with the dependence of the mass of a corpuscle, or electron, upon its velocity. The bare statement of this discovery is startling when viewed from the standpoint of our customary ideas about matter. We are accustomed to look upon mass as an unalterable attribute of matter. Newton's laws of motion—which are the foundation upon which the science of mechanics rests—are based upon the idea of the constancy of mass.

The conception we have formed up to this point of a corpuscle—or an electron—is that it is a particle of matter charged with electricity. This conception involves two unknown quantities—matter and electricity. We all think we know what matter is. We are so familar with matter in its various forms that we are inclined to think it needs no explanation. Of electricity, on the other hand, we think we know less. Familiarity with electric phenomena comes into our lives much later than familiarity with matter, so that we feel that electricity is a mystery compared to matter. It is worth considering very briefly whether this is so or not—whether matter is really a simpler conception than electricity. According to chemists we have to assume some eighty or ninety different kinds of matter—the different chemical elements—so that matter is not a simple conception, by any means. But more than this, for a material view of the universe we have to assume the existence of another kind of matter which differs in its properties from any kind of matter that we are familiar with—the ether. It is true that Lord Kelvin's model for an ether formed of interlocking cog-wheels does help us in realizing the possibility of the existence of a substance with the apparently contradictory properties that the ether must have to fulfill its requirements. And, from another point of view, the attempt has been made to conceive of the atoms of the various chemical elements as built up of the ether. The best known of these hypotheses is the vortex-atom hypothesis of Lord Kelvin. Assuming the ether to be a perfect fluid, a vortex ring formed in it would have the one essential quality we had always believed the atoms to have, absolute permanency. But, with the discoveries in radioactivity, that is no longer an essential, as we have seen. The difficulties in the mathematical analysis involved in working out to its conclusion this hypothesis are too great for our present methods, and so it has remained merely a suggestion. As for

the problem of interpreting electricity in terms of matter, that, too, has remained unsolved. We may speak of an electric charge as a singular point in the ether—a center of strain—but that is not an easy conception to form. And then again we have the baffling problem of gravitation. We know no more today why the apple falls than Newton did.

What I wish to emphasize in all this is, that the attempt to reduce the physical universe to its lowest terms in the form of matter has not been very successful, and while I believe that much more progress can and will be made in this direction, for the present we seem to have reached a point at which we do not know where to turn to make this progress.

Suppose, then, that of our two unknown quantities in the conception of an electron, matter and electricity, we try to explain matter in terms of electricity. For this purpose electricity is a conception that we do not need to explain. It is our fundamental conception from which we are going to attempt to derive matter and the physical universe in general. It is difficult to make myself clear on this subject—mainly because it is not easy for me to conceive of electricity not associated with matter. It is hard to form a conception of anything being more fundamental than matter. But for the purpose of building up a logical scheme for the universe we must try not to let our inherent prejudices blind us to accepting another possibility. And by continual thinking along these lines the time may come when electricity will seem just as simple a conception to us as matter does now.

The goal towards which science aims is the reduction of the physical universe, and all the processes going on in it, to the lowest terms, and for this object it makes no difference whether we take electricity or matter as fundamental. If we find that we can get a consistent scheme for interpreting all the universe in terms of electricity, then electricity will be the fundamental conception —and when that is done it will be time enough to see whether we can go back of our conception of electricity. I do not wish to be understood as promising to exhibit to you any such complete scheme, but I shall try to make clear to you the trend of a large part of modern physics.

The smallest electric charge that has ever been determined is the charge on an electron—or corpuscle. And the smallest mass that has ever been determined is the mass of an electron or corpuscle. Our first question, then, is, can we interpret the mass of a corpuscle in terms of its electric charge?

Suppose, then, that we have what we may call a particle of electricity. Two such particles will repel each other with a force inversely as the square of the distance between them. We cannot make the experiment of measuring the force between two particles of electricity—we can only measure the force between two bits of matter that are charged with electricity. But we first of all make the hypothesis that the force which we can measure is a force between the electric charges. Now merely to say that there is a force between two particles of electricity does not satisfy us. Our minds are so constituted that we must form a picture of something which will transmit this force. We cannot, to be consistent with the view we are now considering, assume a material medium—an ether—pervading all space. For that is equivalent to assuming a kind of matter as a fundamental conception—and we are going to try to get rid of that idea. So we must imagine another way of forming a mental image of the action between the two particles of electricity. Let us, therefore, follow Faraday in assuming that every particle of electricity carries with it lines of force. What these lines of force are we cannot say any more than we can say what electricity is. They are to be for our theory just as fundamental a conception as electricity itself; they are a part of the electric charge. It was proved by Maxwell that all the forces between charged bodies can be interpreted as resulting from a tension along the lines of force and a repulsion perpendicular to them. We shall therefore assume that the lines of force carried by every particle of electricity have this property—of being in a state of tension, like so many stretched elastic bands—and also of repelling each other sideways.

Let us now consider a corpuscle in motion along a straight line. We first suppose that the velocity of the corpuscle is small compared to the velocity of light. Under this condition the lines of force will end on the corpuscle uniformly in all directions. As we cannot suppose that a finite number of lines of force end in a mere mathematical point we shall suppose the corpuscle to be a sphere of radius a, with the lines of force along the radii of the sphere. This leads to a very serious difficulty. If we regard a corpuscle as a very small, but finite, volume of electricity, what is it that keeps it together? If we apply what we know to be the force between two charged particles of matter to the elements into which the finite volume of a corpuscle may be divided, these elements will repel each other, and the corpuscle will fly apart. But since all we really know anything of is the force between

particles of matter containing very many corpuscles, we are not necessarily obliged to assume the same law of force between the elements of a corpuscle. An electric charge in motion is an electric current. An electric current produces a magnetic force, and by Ampere's law the strength of the magnetic force is at any point equal to

$$H = \frac{e\,v \sin\theta}{r^2}$$

where $e =$ charge, v its velocity, r the line from the instantaneous position of the charge to the point at which the magnetic force is required, θ the angle between r and v. Now it is known that the whole amount of work we have to do in order to set up a magnetic field is

$$W = \frac{1}{8\pi}\int\int\int H^2\,dx\,dy\,dz$$

As we suppose the corpuscle to be moving with a velocity small compared to that of light, everything will be symmetrical about it, and we may write this expression

$$W = \frac{e^2v^2}{8\pi}\int_0^{2\pi} d\varphi \int_0^{\pi} \sin^3\theta\,d\theta \int_a^{\infty} \frac{dr}{r^2} = \frac{e^2v^2}{3a}$$

In terms of mass, the amount of work we would have to do to get a particle of mass, m, moving with velocity v, is

$$W = \frac{1}{2}\,m\,v^2$$

Thus we must put

$$\frac{1}{2}\,m\,v^2 = \frac{1}{3}\frac{e^2}{a}\,v^2$$

$$m = \frac{2}{3}\frac{e^2}{a}$$

We have therefore interpreted the mass of a corpuscle in terms of its electric charge.

It should be said that there are other expressions for the mass of a corpuscle in terms of its charge which differ from the one we have obtained. The difference arises from the conception we form of a corpuscle. But they are all of this same form—proportional to the square of the charge and inversely proportional to a length, which we may call the radius of the corpuscle.

The expression we have just obtained holds only when the velocity of the corpuscle is small compared to the velocity of light. When the velocity is comparable to that of light the lines of force are no longer symmetrical with respect to the corpuscle and so our simple method of calculating the energy of the motion can no longer be applied. I fear you will not care to follow me through the rather involved mathematics that is required to work out the case of a corpuscle travelling with high velocity. There are in fact several different theories arising from different conceptions of a corpuscle. But all theories agree in showing that what we have defined as the mass of a corpuscle increases very rapidly with its velocity, and approaches infinity when the corpuscle has a velocity equal to that of light. In other words, it would require an infinite force to get a corpuscle moving with the velocity of light.

It is here that we must appeal to experiment to test the validity of these views. We have seen how it is possible to measure the ratio e/m for the corpuscles, and v, their velocity, by deflecting them from their straight line paths in magnetic and electric fields. Radium emits corpuscles—the beta rays—and there is a wide range in their velocity of emission. Experiments to show a connection between e/m and v for the beta particles from radium were first made by Kauffmann. The experiments have been repeated by others, using also the cathode particles in vacuum tubes. All these experiments show that the ratio e/m decreases with increasing velocity of the particles. For example, Kauffmann found that for a corpuscle travelling with a velocity 2.83×10^{10} cm. per second the value of e/m was 0.62×10^7, while for a corpuscle having the smaller velocity 2.36×10^{10} cm. per second, $e/m = 1.31 \times 10^7$. In other words e/m was more than halved for an increase in velocity of only 20 per cent. Now on the view that electricity is our fundamental conception we must suppose that e, the charge of the corpuscle, remains constant, so that the decrease of e/m with increasing velocity means an increase of the mass of the corpuscle as its velocity increases. This is what theory demands, but the experimental results that have

so far been obtained are not certain enough to enable us to decide absolutely in favor of any one of the various theories that have been developed to account for these effects. But we can say that it appears probable that the mass of a corpuscle or electron can be interpreted as resulting from the motion of an electric charge.

Before leaving this subject something should be said about another possible explanation of the increase in mass of a corpuscle with its velocity. That is a proved experimental result, unless we are willing to suppose that the electric charge diminishes with increasing velocity. What is measured is the ratio e/m; this is found to diminish with increasing velocity, so that either the mass increases or the charge decreases. Well, now, in no view of matter—whether we take matter or electricity as a fundamental conception—is there anything else that would lead us to a possible connection between an electric charge and its velocity. We have seen that there is such a connection between mass and velocity in the view we have described, and there is also a connection between mass and velocity in our older view of regarding matter as the fundamental conception. This connection can be illustrated by a very simple analogy. Suppose we have a solid sphere whose mass is m, moving in a fluid. The fluid is supposed to be perfect, so that there is no loss of energy in friction. The work we would have to do to get the sphere moving with velocity v is $1/2\ m\ v^2$ if there were no fluid. But the sphere sets the fluid in motion, pushing it out in front. The calculation of the energy of this fluid motion is one of the simple problems of hydrodynamics; the result is that the energy of the fluid motion is $\frac{1}{2} m_1 v^2$, where m_1 is the mass of a volume of fluid equal to one-half the volume of the sphere. Everything will then be just the same as if the fluid were annihilated and the mass of the sphere increased to $m + m_1$. At rest the sphere has a mass m; its mass is effectively increased by m_1 when it moves through the fluid. Now according to this, the sphere has one definite mass when it is at rest, another definite mass when in motion and this is the same for all velocities. There is no variation of its mass as the velocity increases. If we suppose that the sphere is not a rigid but an elastic body, such a variation will be found. At rest, the fluid pressure on the sphere is equal in all directions—so that the sphere will not be deformed. In motion, the fluid pressure is unequally distributed over the sphere and it becomes flattened in the direction of motion. The work that has to be done to produce the motion of the fluid may still be written in the form $1/2\ m_1\ v^2$, but m_1 increases with the

velocity—that is, the flatter the sphere gets the greater is its effective mass. On this view, then, we get the result that the mass of the sphere is effectively different for different velocities of motion—increasing with the velocity. If, then, we regard the ether as a perfect fluid, and the electron as a particle of elastic matter, we would get just the effect we wish to explain—that the mass of the electron would increase with its velocity.

This view requires the hypothesis of an ether with all of its apparently contradictory properties. But I have tried to show that as far as explaining the increase in mass with velocity we are not absolutely forced to change our inherent feeling that matter, after all, is the fundamental concept. It may be possible to develop these ideas into a consistent scheme which will be more satisfactory than a scheme which builds matter out of electricity.

Whatever view we take of the electron—whether we assume it to be a particle of matter charged with electricity, or a particle of electricity which is endowed with mass in virtue of its motion—we are forced to the conclusion that electrons have a leading part in the constitution of matter as we know it. So far as we have gone we have found electrons only in vacuum tubes when an electric discharge is passed through, and emitted by radioactive substances. But we must suppose them to have a very wide distribution. For example, when a metal surface is exposed to ultraviolet light, corpuscles are emitted that have all the properties of the electrons that we have studied. So also when metals are raised to high temperatures, electrons are emitted, to such an extent that large electric currents can be sent through the highest obtainable vacuum; the current is carried by the corpuscles shot out from a glowing metal. All these effects point to the existence of these electrons in all forms of matter. From whatever source they come, no differences have ever been found among the electrons, except a difference in velocity, which carries with it a difference in mass. Measurements of the ratio e/m for electrons from different sources, and by varying methods for velocities that are small compared to the velocity of light, do not differ from each other by more than can be accounted for in experimental errors and uncertainties.

We are thus led to the electron theory of matter which assumes that the atoms of the various chemical elements are built up, in part, of electrons. The atoms of the different elements will then differ from each other in the number and arrangement of

the electrons they contain. We shall have more to say about this view of the constitution of the atom, but for the present I am going to speak of some of the consequences of such a view, first of all in relation to light.

The view that electrically charged particles play a part in light phenomena is not a new one. It had been suggested, and some of its consequences worked out, long before the discoveries that led to our knowledge of the actual existence of electrons. Now that the existence of the electron or corpuscle has been made certain, its charge and mass determined, we can use the electrons in optical theory with much more confidence than before. We know that the various chemical elements are characterized by having definite spectra. That is, the atom of any chemical element may be supposed, when it is made, by whatever means, to emit light, to emit light of only certain definite frequencies of vibration. The conception of an atom as an elastic solid, and of the frequencies of the light emitted by it as the frequencies of the free vibrations of an elastic solid, has never led to results at all satisfactory in giving vibrations of the frequencies that we have to account for. Let us see what an electron view of the atom will lead to. All the electrons have the same electric charge, and according to our conventions we call the charge negative. Calling it negative is of course of no significance; it is all a matter of the convention that when a piece of glass is rubbed with silk the glass is called positively, and the silk negatively, charged. And it is found that the electron has a charge of the same nature as the charge on the silk after being rubbed on the glass. Now the idea of an atom formed of negatively charged particles will not work. For the negative electrons are going to repel each other and so we have got to imagine something to hold them together to form an atom. We are thus bound to introduce another fundamental conception along with our fundamental conception of electricity, which, we see, corresponds to negative electricity. This new conception is positive electricity. An element of positive electricity we know nothing of, in the sense that we have a knowledge of an element of negative electricity—the electron. At one time it was thought that the alpha particle might be considered as such. We know that the alpha particle carries a positive charge; but now we know that it is a charged atom of helium and so has a structure comparable in complexity with other atoms, that is, is built up, at least in part, of electrons, so that the alpha particle cannot be regarded as a fundamental unit of

positive electricity. We are therefore forced to assume some special form for the positive electricity and examine the consequences of our assumption.

Let us therefore take positive electricity distributed uniformly throughout a sphere whose size is comparable with the size of an atom; *i.e.* having a radius of the order of 10^{-8} cm. The simplest model for an atom will then be this sphere of positive electricity with a single electron inside it. In order that the atom may be neutral, we must assume the whole positive charge equal to the negative charge. If we call a the radius of the sphere and r the distance of the electron at any instant from its center, the force drawing the electron towards the center is equal to

$$\frac{e^2 r}{a^3}$$

Now the motion of a particle in a circle about a center of force varying directly as the distance is known to be stable, and the time required for the electron to go round the circle once can easily be found.

The equation of motion of the electron is

$$\frac{d^2 r}{dt^2} = -\frac{e^2 r}{m a^3}$$

This is the same equation that we have for the small vibrations of a simple pendulum. The time of complete vibration is therefore

$$T = 2\pi\sqrt{\frac{m a^3}{e^2}}$$

Now we have taken

$$a = 10^{-8}$$

we know that

$$\frac{e}{m} = 1.8 \times 10^7 \text{ in electromagnetic units, or}$$

$$5.4 \times 10^{17} \text{ in electrostatic units}$$

$$e = 4.7 \times 10^{-10}$$

so that

$$T = 4 \times 10^{-16} \text{ seconds}$$

wave length $= T \times 3 \times 10^{10} = 1.2 \times 10^{-5}$ cm.

This is of the order of magnitude of the wave lengths we are familiar with in ordinary light. An electron circulating about inside a sphere of positive electricity would thus give rise to electromagnetic waves of the nature of light waves. It must not be thought that this model for an atom is anything more than a mere suggestion; for one thing, the energy of the electron would be radiated away in the form of light energy altogether too rapidly to allow us to consider this an actual atom. And such an atom would have but one frequency of vibration—only one spectral line—but it is certainly of interest that by such a simple mechanism we can get a wave length of light which is comparable to those that we know are present in ordinary light.

The Zeeman Effect

Of all the applications of the electron hypothesis to optical effects, the most striking success has been in explaining the so-called Zeeman effect. Suppose we have, as a source of light, an incandescent gas, and examine the light through a spectroscope. A number of bright lines are seen, forming the spectrum of the particular gas employed. Now let the incandescent gas be placed in a magnetic field by placing the tube containing it between the poles of a magnet. It is found that, in general, the spectral lines are split up—where there was a single line with no magnetic force acting, on exciting the magnet this line has split up into a number of others. Spectroscopes of very high resolving power have to be used in order to make the distance between the lines appreciable. Some spectral lines split up in a very simple way—either into three lines or two lines, depending upon whether the direction of the magnetic force is perpendicular or parallel to the line of sight. Our simple model of an atom serves admirably to explain this phenomenon. To see how this is let us suppose that we have an electron describing a circular path about the center of an atom. Let it make n revolutions per second. On our simple view of an atom of positive electricity containing a single electron we have seen that

$$n = \frac{1}{T} = 2.5 \times 10^{-17}$$

Now suppose a magnetic force acts on the atom. The electron in motion acts as a current element and therefore the magnetic force H exerts a force on the moving electron which is perpendic-

ular to both the direction of the magnetic force and the direction of motion of the electron. In the accompanying illustration let the outer circle represent the section of the atom, and the inner circle the path of the electron, the arrow showing the direction of its motion. Suppose the magnetic force is directed up from the plane of the paper. Then there will be a force, acting on the electron, tending to drive it towards the center of the atom. This force is $e\,v\,H$, while the force drawing the electron to the center resulting from the uniform positive charge of the atom is $\frac{e^2 r}{a^3}$.

Together, these must give the centrifugal force $\frac{m\,v^2}{r}$. Hence

$$\frac{e^2 r}{a^3} + e\,v\,H = \frac{m\,v^2}{r}$$

But $v = n_1\,2\,\pi\,r$, where n_1 is the number of vibrations in one second under the influence of the magnetic field.

Hence

$$\frac{e^2}{a^3} + 2\,\pi\,e\,H\,n_1 = 4\,\pi^2\,m\,n_1^2$$

For an electron moving in the opposite direction, as illustrated herewith, we get in a similar manner

$$\frac{e^2}{a^3} - 2\,\pi\,e\,H\,n_2 = 4\,\pi^2\,m\,n_2^2$$

Subtracting these two equations, we get

$$n_1 - n_2 = \frac{e\,H}{2\,\pi\,m}$$

The difference in the number of vibrations per second for the two extreme lines into which the single line is split in the magnetic field is thus

$$\frac{e\,H}{2\,\pi\,m}$$

and this may be measured optically. Knowing H, the strength of the magnetic field, the ratio e/m may be found. And the value for this ratio that is obtained in this way, using a number of

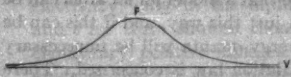
different sources of light, and a number of different spectral lines, is so nearly the same as the value of e/m determined by measurements on cathode particles in vacuum tubes, beta rays from radioactive substances, the corpuscles emitted by metals when exposed to light, or when heated, that we must conclude that light emission is produced by charged particles of the same kind. It is impossible to over-estimate the importance of this result. It furnishes the clearest evidence of the universal existence of the electron and the important part it plays in physical phenomena.

There are more complicated types of the Zeeman effect, where a single line is split up into more than two or three components, and while these cases cannot now be explained satisfactorily, there can be no doubt that the true explanation will be found to depend upon the disturbance in the motion of electrons produced by a magnetic field.

In the theory of light that regards light as the transverse vibrations of an elastic solid ether, and also in the electromagnetic theory of light, there has been a difficulty in accounting for dispersion. Waves of different frequencies travel in material substances with different velocities. The hypothesis was made by Sellmeyer, and developed by many others, including Helmholtz and Lord Kelvin, that there were particles inside matter capable of executing definite vibrations, and that their vibrations so modified the propagation of light through the bodies as to produce the effect of dispersion. These hypothetical particles now have a definite reality. They are the corpuscles or electrons of which we have been speaking. I do not wish to be understood as implying that we are even near a complete theory of the propagation of light through matter, but the fundamental importance of the electron in optical theory is established beyond doubt.

I now wish to consider a point in the general theory of radiation about which we are still very much in the dark. It has to do with the emission of light—or any form of radiant energy—by bodies, when their temperature is raised. The discussion of this question is much facilitated by the introduction of the conception of a "black body." By that is meant a body which absorbs all the radiation falling upon it and reflects none. While an absolutely black body is not known, it is easy to get so close an approximation to one, that an ideal black body is not a difficult thing to imagine. When a black body is raised to a definite

temperature it radiates energy from the shortest known light-waves to the longest known heat waves. The intensity of the radiation, arising from any small range of frequencies, can be measured, and when this is done a curve something like the illustration is obtained; ν is the frequency, the number of vibrations of the radiation in 2π seconds, and F is the intensity of the radiation. The radiation has a maximum value for some definite frequency, and falls off for both higher and lower frequencies. As the temperature is raised, the maximum intensity is displaced towards the higher frequencies—the shorter wave-lengths. It is important to explain why it is that these curves have the form they have, and to deduce an expression which will enable one to calculate the energy, corresponding to any frequency, emitted by a black body at any temperature θ. Such an expression, which does fit the experimental results with great accuracy, was deduced by Planck in 1900:



$$F(\nu\,\theta) = \frac{h\,\nu^5}{4\,\pi^4\,C^4}\,\frac{1}{\epsilon^{\frac{h\,\nu}{2\,\pi\,k\,\theta}}-1}$$

C = velocity of light, h and k absolute constants.

To arrive at this result Planck assumed that the radiating body contained elementary "vibrators" which we can now interpret as vibrating electrons. In addition he had to make the assumption that when energy is absorbed or emitted by an oscillator, it is done, not continuously, but in finite, though very small, elements. These energy elements, the energy quanta, the Germans call them—are something of which it is very difficult to form a conception. We have grown used to thinking of elements of matter: I have tried to show at the beginning of this lecture that we may be forced to conceive of elements of electricity not associated with matter, but I am not going to try to convince you of the possibility of thinking of energy—wholly dissociated from either matter or electricity—flying around in discrete elements. Of course if we find that this hypothesis does explain phenomena that none of our usual views explain, and in addition explains all that is explained by our present views, then we shall be forced to accept the energy-quanta as a working hypothesis. Now, in the first place, Planck has recently shown

that his radiation formula can be deduced on the assumption that radiant energy is continuously distributed through space in wave motion, but that a vibrator, when it emits energy, does so in finite elements, although it absorbs energy continuously. It does not seem wholly improbable that a model for an atom can be thought of which will behave in just this way, and if this can be shown, the conception of the energy-quanta will be unnecessary so far as accounting for the radiation law is concerned. There can be no question about the energy-quantum hypothesis explaining certain phenomena—especially in connection with the specific heat of bodies, and the photo-electric effect, that have never received any other explanation. But it is by no means certain that this hypothesis is necessary to explain these phenomena. Aside from the difficulty of conceiving of these energy-quanta there is one very serious difficulty in accepting this hypothesis. In accepting it we are obliged to give up the wave theory of light. We should have to go back to what amounts to Newton's corpuscular theory of light, Newton's corpuscles being replaced by these particles of energy. Now so far as we know, such a theory cannot account for some of the most striking properties of light—interference, diffraction, polarization—things which the wave theory of light explains so beautifully. The success of the wave theory of light, not only in explaining known phenomena, but in predicting new phenomena, has been so great that the energy-quantum hypothesis requires very much more evidence in its favor than has yet appeared, before it can be accepted.

Positive Electricity

I now wish to speak about one of the most puzzling features connected with our present views. It has to do with the nature of positive electricity. Negative electricity, we have seen, may be regarded as having an atomic structure, being composed of discrete particles, called electrons or corpuscles. And I have tried to convince you that these corpuscles have a real existence, as real as anything we know about. Negative corpuscles, whatever their origin, all are identical, save for differences in their velocities. One would rather expect to find something similar for positive electricity. But nothing of the sort has ever been found. Positive electricity, whenever it appears, is always associated with atoms or molecules of the chemical elements. We have already spoken of a sphere of positive electricity, but this was introduced solely for the purpose of enabling us to build up an atom of

ordinary matter out of electrons—we had to assume some means of holding the negative electrons together, to keep them from repelling each other by the forces between like charges.

So far, we have become acquainted, in nature, with positive electricity, only in the alpha particles; measurements of e/m and e for them showed them to be atoms of helium with two elementary positive charges. And we also have more direct evidence that the alpha particle on losing its charge becomes an atom of helium. We must now speak of some other occurrences of positive electricity. As from radioactive substances both negative and positive charges are emitted, so in vacuum tubes, when an electrical discharge is maintained in them, we find both cathode rays, which are formed of negative particles, and the anode rays, which are formed of positive rays. If the cathode is perforated with a number of holes, a luminosity is observed behind it. Experiment shows that this luminosity is caused by a stream of positively charged particles, and determinations of the ratio e/m for these particles have been made by methods similar to those employed for the cathode particles. The results of measurements of this kind show that e/m is very much smaller for these positive particles than for the negative corpuscles. This may be interpreted either by assuming that the charges the positive particles carry are much smaller than the charges carried by the corpuscles, or that their mass is very much greater. Now, no negative charge has ever been found smaller than the charge carried by the corpuscle. It seems reasonable to suppose, therefore, that this is also the smallest positive charge that can exist. Assuming this, the observed values of e/m give values for the masses of the positive particles which indicate that they are either single atoms of various chemical elements or aggregates of two or more atoms. For example, the largest value of e/m found is just what would correspond to a single hydrogen atom, carrying a single positive charge. With mercury vapor in the discharge tube, values of e/m are found which would correspond to four mercury atoms, with a single positive charge. And atoms of other chemical elements are detected in the same way. Sir J. J. Thomson, who has contributed a large part of our knowledge of these positive rays, regards the method of determining e/m for these particles as an extremely sensitive method of chemical analysis. The presence of minute traces of a gas may be shown—a far less proportion than would be required to make its presence known by spectroscopic means.

The view which these results lead us to take of the atoms of the elements, is, then, this. We assume positive electricity distributed throughout a volume, for simplicity a sphere, of atomic size. In this sphere of positive electricity there are just enough negative corpuscles to neutralize the positive electricity. Such an atom may expel one or two negative corpuscles without necessarily changing its character thereby—that is, it still remains an atom of the same element, but now positively charged in virtue of having lost some of its negative electricity. The corpuscles may subsequently be picked up again, when the atom becomes once more electrically neutral.

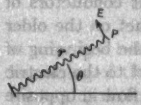
Let me summarize briefly the main points of what I have tried to exhibit. In the first place we considered the negative corpuscle, showing that its mass might be interpreted as resulting from a negative charge in motion, although we were not absolutely forced to this conclusion. The universal occurrence in nature of these corpuscles was next brought out, and their fundamental importance in phenomena connected with light proved; the energy-quantum hypothesis was next briefly touched upon, showing why it had been introduced. Finally the nature of positive electricity was discussed, leading to a provisional view of the structure of the atom.

LECTURE V

Before beginning on the subject announced for this lecture I must, in order to answer questions that have been raised, give a little further account of some of the things dealt with in the previous lecture. You will remember that I described a model of an atom, consisting of a sphere of positive electricity, with a single negative electron moving in a circle inside. The question is, why is it that this emits light? We believe now in the electromagnetic theory of light, according to which light consists of a periodic electric force and a periodic magnetic force, at right angles to each other, propagated by wave motion in a direction at right angles to both the electric and magnetic force. A mathematical calculation, which it would take too long to give here, shows that for points which are at a great distance from the vibrating electron compared to the dimensions of its orbit, this is just the state of affairs that we have—magnetic and electric forces, perpendicular to each other, propagated outwards in waves with the velocity of light. It may puzzle you to understand why it is that the velocity of light enters into the solution

of a purely electrical problem like this. It is because we measure electric and magnetic forces each in a particular set of units—in a problem like the present one, where both electric and magnetic forces enter, they must be reduced to the same system of units. This requires the introduction of a factor, which experiment proves is equal to the known velocity of light in space. Theory shows that the electromagnetic effects are propagated with a velocity equal to the ratio of the units in the two systems, and this ratio is the velocity of light.

A convenient way of thinking of these effects is in terms of lines of force, which we may imagine are carried by the electron, are, in fact, a part of it. Think of these lines of force as so many stretched threads, one end of each attached to the electron. We must assume that transverse waves travel along these strings with the velocity of light. Now suppose that the electron moves in a circular orbit. We know that motion in a circle may be compounded of two motions in straight lines perpendicular to each other. It is only the component at right angles to the line of force which is effective in causing its transverse vibrations, and so we may neglect the other component. Therefore at any point at a distance from the electron the line of force will vibrate back and forth in a direction perpendicular to itself when at rest. The sketch herewith illustrates roughly the spreading out of the transverse electric force along one line of force. We therefore have a vibrating electric force, which at every point is perpendicular to the line joining the electron to the point. Accompanying this there is a magnetic force perpendicular both to the line joining the electron to the point and to the electric force. This therefore results in a spherical wave of electric and magnetic force spreading out from the electron.



Metallic Conduction

Let us now consider what influence the discovery of the electron has had upon our views of the conduction of electricity through metals. First of all it may be well briefly to consider our previous notions of metallic conduction. It had to be assumed that electricity was something—a substance or an effect—that travelled freely through conductors. The force driving the electricity was called the electromotive force, and the flow of electricity the

electric current. Between these two quantities a simple relation, Ohm's law, was found to hold, which we may express by

$$i = k E$$

or, in words, the electric current is equal to the conductivity k, times the electromotive force. The conductivity k is a specific constant for each kind of conductor. Experiment shows, however, that the conductivity of a conductor is not constant, but depends on its physical state. Thus on heating the conductor, in general, the conductivity diminishes; some metals shows the opposite effect, and this makes it possible to make alloys whose conductivity varies very little with the temperature. In a magnetic field, again, the conductivity may increase or decrease, depending on the conductor and the direction of the magnetic force with respect to the current. Light falling on certain conductors, notably selenium, changes very decidedly their conductivity. Then, too, there was found to be a very close connection between the electric conductivity and the heat conductivity of metals. The old view of an electric current offered no explanation of this variation of conductivity with the physical state of the conductor. It merely had to be accepted as a fact. The best conductors of heat were found, in general, also to be the best conductors of electricity. There was no explanation of this fact on the older view. It is true that Wilhelm Weber towards the beginning of the last century offered an hypothesis in regard to the electric current in which the current was regarded as the flow in opposite directions of positive and negative electric particles, and by making additional hypotheses in regard to the nature of these particles many of the known phenomena might be accounted for. But as long as there was no evidence of the reality of these particles this view never received general acceptance, nor was developed to any considerable extent.

We are still far from being able to give a completely satisfactory explanation of the various phenomena with which we are concerned, but a considerable amount of progress has been made in applying the notion of electrons to metallic conduction, and I shall attempt to give some account of this in its simpler aspects.

The view we have been led to take of an atom is that it is a volume of positive electricity containing many negative electrons. Now we have good reasons for believing that in a metal, in addition to the electrons contained in its atoms, there are also many electrons not contained in them, but continually moving about

among the atoms. We may look upon these electrons, the free electrons we shall call them, as pursuing zig-zag paths among the metallic atoms, colliding with them—perhaps entering into them, while others are shot out from the atoms. On the average there will be a certain number, N, of these free electrons per unit volume. These have a perfectly irregular motion, there are just as many moving in one direction as another. Now suppose an electric force is applied to the conductor. This we know causes a current to flow through it. Let E be the electric force. There is now a force $e\,E$ acting on each electron driving it in a direction opposite to the direction of the electric force. Negative electricity flowing in one direction is equivalent to positive electricity flowing in the opposite direction. We thus get an electric current flowing in the direction of the electric force. It is worth while to calculate the strength of this electric current on the simplest view we can take. Let v be the velocity of the electrons before the electric force was applied. The velocity of an electron in a direction opposite to that of the electric force is given by

$$m\frac{d^2x}{dt^2} = e\,E$$

$$\frac{dx}{dt} = \frac{e}{m}\,E\,t$$

at any time between two collisions of the corpuscle. But at the beginning of the free paths the corpuscles had no average velocity in this direction; at the ends of their free paths the electrons thus have a velocity $e/m\ E\ T$ where T is the time the electron is free. So the average velocity in this direction is

$$\frac{1}{2}\frac{e}{m}\,T\,E = V$$

In a unit volume of the metal we have N free electrons; each carries a charge e, and each moves with this average velocity in a direction opposite the electric force. Therefore the electric current is equal to all the charges that cross the section of the conductor in unit time. Let the cross-section of the conductor have unit area. Then the number of electrons which cross it in unit time will be equal to the number that at the beginning were contained in the volume V, *i.e.*,

$$\frac{1}{2}\frac{e}{m}\,T\,E\,N$$

Each has a charge e, so that the current is

$$i = \frac{1}{2}\frac{e^2}{m} T N E$$

We thus get Ohm's law, the conductivity being

$$k = \frac{1}{2}\frac{e^2}{m} T N$$

Let us now introduce an hypothesis which we shall attempt to justify by its consequences. It is that the electrons move about among the atoms of the metal just as the molecules of a gas move about, and just as the average kinetic energy of a molecule of a gas is proportional to its absolute temperature, θ,

$$\frac{1}{2} m v^2 = \alpha \theta$$

so the average kinetic energy of an electron is proportional to the absolute temperature, with the same factor of proportionality, α.

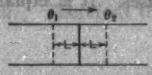
Then since $T = \frac{L}{v}$, where L is the average distance the electron goes between collisions—the free path of the electron—we can write

$$k = \frac{1}{2}\frac{e^2 L}{m v} N = \frac{e^2 v N L}{4 \alpha \theta}$$

Experiment shows that the conductivity of most pure metals varies very nearly inversely as the absolute temperature. This is what our formula tells us, provided that $N L v$ does not vary with the temperature. On our hypothesis, v varies as the square root of the temperature, so that we may assume that $N L$ varies inversely as the square root of the temperature. We have not time to consider the different views that have been held on this matter; the point I wish to emphasize is that the view of metallic conduction that has been briefly described, does lead, first of all, to Ohm's law, and it does account for a variation of conductivity with the temperature. The old idea of the electric current made no attempt to give any explanation.

Let us now find the conductivity for heat of our metal. For this purpose we must calculate how much heat goes through any unit cross-section in a unit time. Let the temperature decrease

as we go from left to right. The number of electrons that cross any cross-section in unit time is $\frac{1}{6} N v$. For v is the distance they travel in unit time and as they move in all directions one-sixth of those in a volume v will get through. Each electron has an amount of energy $\frac{1}{2} m v^2 = \alpha \theta$. For θ we must take the temperature at the last collision. On the average, the last collision was at a distance L to the left of A. Call the temperature at this place θ_1. Hence the heat crossing A in unit time from left to right is



$$\frac{1}{6} N v \alpha \theta_1$$

Similarly the heat crossing A from right to left is

$$\frac{1}{6} N v \alpha \theta_2$$

Hence the net amount of heat that crosses A from left to right is

$$\frac{1}{6} N v \alpha (\theta_1 - \theta_2)$$

or

$$\frac{1}{3} N v \alpha \frac{\theta_1 - \theta_2}{2 L} L$$

$\theta_1 - \theta_2$ is the difference in temperature at two places distant $2 L$ from each other; $\frac{\theta_1 - \theta_2}{2 L}$ is therefore the rate of fall of temperature as we go along the bar. Hence the heat conductivity is

$$c = \frac{1}{3} N v \alpha L$$

The ratio of the electric to the heat conductivity is

$$\frac{c}{k} = \frac{4}{3} \frac{\alpha^2}{e^2} \theta$$

This result is of particular interest because the only quantity in it which can vary with the temperature is θ, the temperature itself. The ratio of the heat to the electric conductivity should then increase proportionately to the absolute temperature. Suppose we put in the known values of the quantities in this equation.

We have found that

$$e = 1.6 \times 10^{-20} \text{ in electromagnetic units.}$$

Now α is known from the kinetic theory of gases. It is equal approximately to

$$1.8 \times 10^{-16}$$

Then at 0 deg., $\theta = 273$

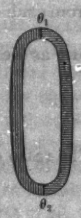
$$\frac{c}{k} = 4.6 \times 10^{10}$$

Experiment shows that this ratio, for a large number of metals, is about $6 - 7 \times 10^{10}$. In our calculation, it has been assumed that both the thermal and electric currents are carried only by the negative corpuscles. It is almost certain, however, that the thermal conductivity is partly due to the motion of the atoms themselves inside the metal. This would tend to increase the ratio c/k, bringing it nearer to the known value determined by experiment.

This result is as remarkable as those obtained by the application of the theory of electrons to optical phenomena that we considered in the last lecture. It furnishes very strong confirmation of the view that the electron plays an important part in electric conduction in metals.

Thermoelectric Effects

If a circuit is made of two different metals, and the two junctions are kept at different temperatures, it is known that a current will flow around the circuit. Let us see how the corpuscular theory accounts for this effect. We have taken the view that the corpuscles move about in a metal just as molecules of a gas in an enclosed space. And just as the pressure which a gas exerts is a result of the impacts of the molecules, so there will be a pressure at any point in a metal due to the impacts of the corpuscles. To calculate this pressure we need only to consider the momentum which the corpuscles bring up to a unit area in unit time. On the average we can say that one-sixth of all the corpuscles are moving in a given direction. Each has momentum mv. The momentum of the corpuscles striking a unit area of the wall in unit time will therefore be



$$\frac{1}{6} m v^2 N$$

If we assume that the corpuscles are reflected from the wall without loss of energy, each carries away an amount of momentum $m\,v$, but in the opposite direction from that it brought up to the wall. Therefore the wall receives in unit time the momentum

$$\frac{1}{3}\,m\,v^2\,N$$

But this must be the pressure the corpuscles exert. Hence

$$p = \frac{1}{3}\,m\,N\,v^2 = \frac{2}{3}\,N\,\alpha\,\theta$$

If now the number of free corpuscles in unit volume is different for different metals, at a junction between two metals there will be a difference in the pressure of the corpuscles on the two sides and so the corpuscles will move from one metal to the other. To make the case definite suppose that N_1 is greater than N_2 and θ_1 is greater than θ_2. Then at the hot junction there will be a difference in pressure of

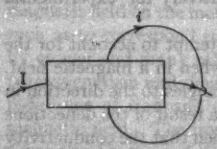
$$\frac{2}{3}\,(N_1 - N_2)\,\alpha\,\theta_1$$

driving the corpuscles from 1 to 2. At the other junction there will be a difference in pressure

$$\frac{2}{3}\,(N_1 - N_2)\,\alpha\,\theta_2$$

also driving the corpuscles from 1 to 2. But this is less than the former difference in pressure and so there will be a continual flow of corpuscles from 1 to 2 at the warm junction and from 2 to 1 at the cool junction. There will be therefore an electric current flowing in the opposite direction.

The other thermoelectric effects—the Peltier effect, the Thomson effect—may be explained qualitatively equally well by the corpuscular theory.



Let us now consider some effects of magnetism on electric conductivity. According to the views of Maxwell, if a conductor carrying an electric current is placed in a magnetic field, a mechanical force is exerted on the conductor, but there is no effect on the electric current.

It was discovered by Hall that if the conductor were in the form of a thin plate, through which a current I was sent in the direction indicated, and a magnetic force applied perpendicularly to the plate, then a current was produced in the circuit i. With no magnetic force acting, there is no current in this circuit. The existence of such a transverse current can easily be accounted for on the corpuscular view. Acting on a corpuscle there is a force at right angles both to the direction of the magnetic field H, and to the direction of motion. This force deflects the corpuscles from the right to left motion so that some of them move through the branch circuit, thus producing an electric current in the opposite direction. We meet, however, with a difficulty here.

According to what we have just seen, the Hall effect should have the same sign for all metals. But as a matter of fact for some metals the transverse current has the direction indicated by this theory; for other metals the transverse current has the opposite direction. This variability could be accounted for if we assumed that, in addition to the negative corpuscles, the current was also carried, in part, by positive charges; these would result in a transverse current opposite in sign to the current carried by the negative corpuscles and so, depending upon which effect was the greater, the Hall effect would have one sign or the opposite. But we have very strong evidence that positive charges are always associated with atoms and so we cannot assume them to have mobility enough in a metal or other solid to take an appreciable part in electric conductivity. We must therefore seek another explanation. The explanation is to be found, I think, in the structure of a metal. We have assumed far too simple a structure for the interior of a metal. In our calculations we have considered only the free electrons—that is, those that are outside of the atoms. It is probable that the corpuscles in the atoms play a part in these effects, although we have no theory yet which will account quantitatively for experimental results.

A similar difficulty is met when we attempt to account for the change in the conductivity of a metal when in a magnetic field. If the magnetic force is applied at right angles to the direction in which the electric current flows, then as a result of the deflections of the paths of the electrons it is easily seen that the conductivity of the metal will be decreased. This is the result that is observed, except that with the magnetic metals, iron, nickel and cobalt,

weak magnetic fields decrease the conductivity; but on increasing the magnetic force the effect changes in sign, so that with strong fields the conductivity is increased. On this simple view there should be no effect on the conductivity when the magnetic force is parallel to the current. Experiment shows, however, that, in general, there is a decrease in the conductivity in this case. Qualitatively, both these departures from our simple theory can be explained by assuming that the effect of the magnetic field is to produce a rearrangement among the atoms so as to alter the free paths of the electrons. That some such effect should exist is probable. Recent work in metallography has shown that metals have a very complicated structure—being in fact aggregates of crystals. The view we have taken of a metal is undoubtedly far too simple and it is much more to be wondered at that this simple view should lead to so many striking confirmations than that departures from it are observed.

A number of attempts have been made to explain magnetism on the electron hypothesis. At first sight it seems an easy thing to do. We generally look upon a magnetized body as an assemblage of small magnets which are all made to turn more or less in one direction when a magnetic force is applied. Now the fundamental theorem in electromagnetism is that an electric current flowing in a small closed circuit is equivalent, as far as external effects go, to a small magnet, whose axis is perpendicular to the plane of the current. As an electron in motion is equivalent to an electric current, the electrons circulating in closed orbits inside the atoms might be expected to make the atoms themselves elementary magnets. This would be just the result necessary to account for the magnetism of such substances as iron and also the so-called para-magnetic substances—which have similar magnetic properties but in a much smaller degree. However, when one considers the possible symmetrical distribution of electrons in the atoms, it is found that the atoms will not be elementary magnets. There will still be an effect arising from the magnetic field on the motion of the electrons inside the atoms and such as to correspond to diamagnetism—the property exhibited by copper and many other substances. The difference between paramagnetism and diamagnetism may be shown by taking two rods—one of iron and one of copper, suspended in a uniform magnetic field. The iron tends to set itself so that its length is along the direction of the magnetic force, while the copper tends to set itself at right angles to the magnetic force. Thus, on this

view, the atoms of all substances would be diamagnetic. To account, then, for paramagnetism, it is necessary to assume that the atoms, owing to a lack of symmetry, are effectively elementary magnets, as a result of the circulating electrons. The theory has been developed along these lines by Langevin, who finds that the diamagnetism will be independent of the temperature while paramagnetism varies inversely as the temperature; and this agrees, in general, with experimental results. We thus have every reason to believe that a real explanation of magnetism is to be found in the electron theory.

It will not be out of place here to say a word regarding the essential difference between a conductor of electricity and an insulator. In a conductor we have seen that we may assume that, in addition to the electrons circulating in the atoms, there are also free electrons. A metal atom may be looked upon as one from which one or two electrons can escape, and these escaped electrons then become free electrons. An atom of an insulator, on the other hand, we may regard as one in which the electrons are more firmly held, so that in a perfect insulator there will be no free electrons.

At the beginning of these lectures I told you that I was going to try to show how far recent discoveries had changed our old ideas about the constitution of matter. It may therefore be well to give a very brief summary of the most important results.

In the first place we have learned that the atoms of the various chemical elements are complicated structures. One constituent which is common to all atoms is the negative electron or corpuscle. In addition we have to assume positive charges as well—as to what their nature is we are still very much in the dark. As for the number of corpuscles in the atom, various lines of reasoning give results that show that this number must be comparable to the atomic weight of the atom. One method of getting an estimate of the number of corpuscles in an atom is by calculating the absorption that a stream of beta particles undergoes when traversing a known thickness of matter. This is something that can be determined experimentally, and by assuming that the absorption of beta particles is the result of collisions with the corpuscles in the atoms, an estimate of the number of the latter may be obtained. So that we cannot assume the whole mass of an atom to be the sum of the masses of the electrons contained in it. We are led, therefore, to assume that the mass of the atom is concentrated in the positive part of the atom. We may take a

provisional view of the atom something like this—a number of positive charges with just enough negative corpuscles circulating around them to neturalize the electric charge. Atoms built in this way will have different degrees of stability. Such an atom may lose or gain one or two corpuscles and still remain the same kind of an atom. It will then correspond to a very stable element. Or an atom may be so unstable that on losing an electron a complete rearrangement takes place, resulting in a wholly different atom. That will correspond to a radioactive atom. This view of the atom leads to a natural explanation of chemical combination. Say that we have two different atoms A and B. A may lose an electron, leaving it positively charged. B may gain the electron lost by A. B is then negatively charged. A and B will then be attracted to each other and they may combine to form a molecule of two atoms $A\,B$.

The weakness in the position where we stand at present lies in our ignorance of the nature of positive electricity. Negative electricity distributed in corpuscles, we know a great deal about. We have seen something of the universal importance of the negative corpuscle in optical, thermal, and electric phenomena.

We have seen that the mass of the negative corpuscle may be interpreted in terms of an electric charge in motion, that its mass increases with increasing velocity. So we are led to think that perhaps all mass is electrical in its nature. We cannot, however, have much confidence in this view until something analogous is proved for the unknown positive charge.

Besides the change in our ideas regarding atomic structure which has resulted from the study of radioactivity, there is another much more revolutionary trend in modern thought concerning the physical universe. This has to do with the very foundation of the science of mechanics. If what has apparently been proved for the negative corpuscle, that its mass increases with its velocity, holds for all matter, then our familiar laws of mechanics, which have been accepted as holding absolutely, can be regarded only as approximations. It is only when the velocities we consider approach that of light that there will be any appreciable departure from the motion given by applying Newton's laws. According to our usual ideas, if a constant force acts on a body, a certain definite momentum, the product of the mass by the velocity, will result. If the force acts twice as long, double the momentum will result. The mass being constant, there will be no limit to the velocity that the body may acquire.

It is only necessary to apply the force for a sufficiently long time. But this is not so if the mass increases with the velocity. Doubling the time the force acts will not double the velocity, since the mass also increases. In the case of a corpuscle, when we regard its mass as resulting from a charge in motion, the mass becomes infinite when its velocity is equal to that of light. If the same be held to be true for all matter, if, in other words, all mass is of an electromagnetic origin, then the velocity of light is the highest velocity we can conceive of. This is a result which is startling when viewed from the standpoint of our usual ideas of mechanics. According to this view, the velocity of light in space is a constant of fundamental importance in the whole domain of the physical sciences.

All of this is intimately related to what has come to be known as the principle of relativity. If it is assumed that the velocity of light in space is the highest velocity that can be attained, it must be impossible to detect absolute motion of a system by any experiments made in that system. Suppose, for example, the velocity of light be measured on the earth, first in the direction in which the earth is moving about the sun, and second, in a direction at right angles to the motion of the earth. In the former direction the velocity of the earth would be added to the velocity of light, and the sum would be a velocity greater than that of light. But this, by hypothesis, is impossible. Hence it would follow that by no experiment in a moving system can we detect the absolute motion of that system. All that can be detected is the motion of one system relative to another.

A number of experiments have been made with the object of detecting absolute motion. The best-known of these is the Michelson-Morley experiment, in which a difference in the velocities of light, traveling along and perpendicular to the motion of the earth, was looked for. All such experiments have given negative results. And these negative results have led to the enunciation of the principle of relativity, according to which the absolute motion of a system cannot be determined by any experiment made in that system. In this form, the principle of relativity is a principle of negation, like two other fundamental physical principles—the principle of the conservation of energy and the second law of thermodynamics. The former denies the possibility of perpetual motion, and the latter denies the possibility of transferring heat from a cold to a hot body by any self-acting mechanism.

From a certain point of view, the principle of relativity, stated in this way, would seem to be a necessary consequence of the electromagnetic origin of mass. If all matter can be considered to result from the motion of electric charges, it must follow that absolute motion cannot be determined. For without motion, there could be no matter, and without matter there would be no possibility of detecting motion.

However, the necessity of introducing the principle of relativity with all of the consequences, so opposed to what we have always assumed as fundamental truths, that have been held to follow from it, cannot be said to be proved. Speculation regarding it has proceeded rather farther than experimental results warrant. The subject is mentioned here only for the purpose of showing how deeply into our fundamental conceptions of the physical universe the study of radioactivity has led.

In conclusion, let me repeat what may be taken as the main results of the study of radioactive phenomena. First, we are forced to believe that the atoms of the elements are dynamical systems of varying degrees of stability. In the second place, the negative corpuscle, or electron, has been shown to be of fundamental importance in the whole domain of the physical sciences. The difficulties in developing further these views of matter, for which a foundation has been laid, center about two large problems: the nature of positive electricity, and the old problem of the ether.

From a certain point of view, the principle of relativity might in this way, would seem to be a necessary consequence of the electromagnetic basis of mass. If all matter can be considered to result from the motion of electric charges, it must follow that absolute motion cannot be determined. For without motion, there could be no matter, and without matter there would be no possibility of detecting motion.

However, the necessity of introducing the principle of relativity with all of its consequences, in contrast to what we have always assumed as fundamental truths, that have been held to follow from it, could not be said to be proved. Investigation regarding it has proceeded rather farther than experimental results warrant. The subject is mentioned here only for the purpose of showing how closely this and fundamental considerations of the physical universe the study of radioactivity has led.

In conclusion, let me repeat what may be seen as the main results of the study of radioactive phenomena. First, we are forced to believe that the atoms of the elements are dynamical systems of varying degrees of stability. In the second place, the negative corpuscle, or electron, has been shown to be of much more important in the whole domain of the physical sciences. The difficulties in developing further these views of matter, for which a foundation has been laid, centre about two large problems: the nature of positive electricity, and the old problem of the ether.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

PURCHASED POWER IN COAL MINES

BY H. C. EDDY

The ideal corporation may be defined as a cooperating aggregation of individuals of specialized ability.

The practical application of this idea has produced industrial companies whose activities frequently become so extensive and so diversified as to make it desirable to separate them into component parts, each exercising those functions which it is especially fitted to perform. Thus we find the huge industrial organizations of today made up of a number of departments, each complete in itself and each virtually a corporation, in the sense of the definition given above.

This division and segregation of corporate activities is practicable only in comparatively few instances, as the cost of thoroughly competent heads of departments becomes too great a burden for the companies of less than extraordinary size to carry. In the majority of cases it becomes good business policy to carry out this division of effort by depending upon outside agencies, whose sole function is to supply, in the most economical way, some certain requirement.

Thus the function of the public utility companies becomes that of supplying transportation, the facilities for the transmission of intelligence and the distribution of electricity, water and gas, each a highly specialized branch of service calling for the expenditure of much capital, technical knowledge and broad-gage thought, to reach the fullest possible development.

There is then a sound fundamental basis for the existence of an organization whose sole business is to make and sell power in both large and small quantities.

However sound the abstract theory of the central station as a power merchant may be, its continued existence depends upon its ability, in practise, to supply power on a basis which shall be reasonably profitable to both parties concerned in the transaction.

An analysis of the conditions of use of power in the bituminous coal mines in Pennsylvania and Ohio discloses certain general facts which are decidedly favorable to the purchase of power, when available, as compared with the operation of independent plants.

There are but few mines in these fields that operate more than sixteen hours per day, and many that run but a single shift. The double shift basis of operation is, however, sufficiently common to be considered typical. The load curve of such a mine shows that approximately two-thirds of the total kilowatt hours per day of twenty-four hours, is used between 7 A. M. and 4 P. M., the remaining one-third being used between 6:30 P. M. and 1 A. M. During the day run the demand is quite variable, fluctuating between wide limits for short periods. The widely different conditions existing in the individual mines makes it practically impossible to give accurate values to the various elements of load. In one mine the grades may be in favor of the loads to be hauled by the locomotives, while in another case the reverse may be true, tipples may be above or below the level of the mine opening, fan operation may be required continuously at a high rate of air discharge or the reverse. Notwithstanding all these variables, the general characteristics of the total load are quite uniform in being removed from the central station peak.

The application of alternating-current motors to mine equipment is not general, practically all mines operated by electric power using direct current at either 250 or 550 volts. This necessitates the use of either synchronous converters or motor-generator sets when power is purchased. When the latter are used it is the general practise to specify synchronous motors, on account of the somewhat better efficiency to be obtained, as compared with induction motors, and also for the improvement of power factor.

The advantages to the central station which justify low prices for mine power, may therefore be summed up as follows:

The considerable amount of power used.

The " off-peak " load.

The extensive application of synchronous motors, tending to raise the plant power factor, with the attendant advantages.

From the standpoint of the mine operator the advantages of purchased power are more numerous.

The most important consideration is that of cost. It is obvious that in this presentation of the subject, no comparisons of actual figures can be made, but it lies within the province of the writer to indicate the essential reasons for a relatively high cost of operation of independent mine power plants.

The controlling element lies in the load factor, which may be defined as the ratio of average use of the equipment required to meet the maximum load conditions.

The daily load factor is much higher than the monthly ratio, due to the fact that during the month the average number of working days ranges from 15 to 20, due to car shortage, market conditions and temporary labor difficulties. The annual load factor is even lower, due to the same general conditions, but upon a more extended basis.

The result of this condition is that the investment in power plant and equipment is idle for much of the time, and as interest, depreciation and taxes are continuous charges, the result is that the actual output of the plant carries a very high fixed charge per kilowatt hour.

This condition does not exist when power is purchased, except in so far as it applies to the current transforming apparatus. The cost of equipment per kilowatt of capacity being much lower than the cost of complete plant equipment, there is a substantial saving to be effected in this item of power costs.

The actual manufacturing cost, exclusive of overhead charges, under conditions of widely varying load and intermittent use of generating equipment, becomes much higher than would be found with exactly the same apparatus working more continuously.

The individual mine plant is usually located at the least favorable point, considered electrically, *i. e.*, at the mouth of the mine. As the mine is developed the electrical center of the load recedes from the plant location and the losses in the distributing system constantly increase. The extent to which it is advisable to increase the investment in copper to minimize voltage losses can be determined only by a careful survey of the conditions applying to each particular installation.

Aside from the actual copper loss, the low voltage obtainable

at the point of delivery of current brings in its wake a high maintenance cost for motors on locomotives and coal cutters, chiefly in the form of armature and commutator repairs. These troubles are directly traceable to the abnormal volume of current required by reason of the less than normal voltage. Aside from this actual expense there is the loss of possible output due to reduced capacity of motors brought about by the unfavorable conditions of current supply. This loss is far greater than the actual cost of repairs and its magnitude is often unappreciated by mine operators.

These conditions may be remedied to a great extent, if not practically eliminated, where power is purchased, by placing converters or motor-generators so that the mine distributing system may be fed at several points, thus materially reducing line losses, equalizing line voltage, and bringing it up to the normal working voltage of the motors in use. As the mine is developed and new conditions arise with respect to the distributing system, the location of the conversion equipment may readily be changed. This flexibility is impossible with a complete steam plant.

In any successful concern the growth of its operations is ordinarily greater than originally expected. The coal mining industry is no exception to this general rule, and operators are periodically faced with the proposition of extending and enlarging individual plants to meet the greater demands for output. Usually this problem is solved by adding boilers, engines and generators, with a resulting greater investment of capital than would be required by the addition of a motor generator set. The capital invested in plant equipment in excess of the cost of motor generators would earn much more per year, if put into strictly mining machinery.

The operators of mine plants are ordinarily handicapped by the character of labor available for power plant operation. In some cases mines are so located with regard to living conditions that really skillful engineers may be obtained and kept. In more instances, however, the conditions of work and locality of the mines do not prove attractive to the best men except as a temporary expedient. It is more often than not, a case of a more or less regular procession of engineers through the cycle of being hired, endured and "fired." As a natural result the average mine plant receives less than an ordinary amount of skilled attention, when, by reason of the severe conditions under which it

operates, it should receive more. Under such circumstances it is to be expected that the cost of maintenance and repair will be high. Aside from labor conditions the item of boiler repairs and replacement is usually excessive on account of the bad water conditions that are so commonly found in the coal districts.

Where power is purchased, the care required by conversion apparatus does not call for an expert man in constant attendance. The ordinary daily care required may be furnished by the necessary switchboard operator. In some cases this duty can be safely assumed by the repair shop men, thus eliminating entirely any cost for attendance.

It is obvious that the employers liability hazard, so far as power supply is concerned is greatly reduced when power is purchased than when a steam plant is operated.

The tendency of labor and other costs entering into the production of power is upward. This can only be met and compensated for in the case of the central station through the use of generating equipment of the very highest economy, by the securing of business of a diversified character of use, enabling the operation of the plant under good load conditions each hour of the twenty-four, and through quantity production. These safeguards against increasing power costs cannot be obtained by the individual plant operator except through the protection afforded by a long term contract with a substantial and responsible central station organization.

The advantages gained by the mine operator by the purchase of power are direct and may be summed up as follows:

Reduction of fixed charges on investment.

Reduction of actual operating costs due to the fact that only power used is paid for, without stand-by charges due to intermittent operation, and by reason of the higher efficiency of electrical apparatus at any load, as compared with steam generating equipment of the character available for mine work.

Material reduction of distribution losses.

A considerable increase in the output of mining machines and locomotives due to maintenance of speed through normal voltage.

Flexibility of location of motor-generators, enabling them to be placed at points giving the best operating results, and to be readily and cheaply moved as conditions change.

Reduction of labor costs for attendance.

Elimination of high maintenance, repair and replacement costs for boilers, piping and engines.

Reduction of cost of superintendence, enabling the mine superintendent to devote his entire attention to securing output.

Reduction of liability.

Insurance against constantly increasing power costs, through term contracts at fixed rates.

Additional coal available for sale.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers. Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

CENTRAL STATION POWER FOR COAL MINES

BY C. W. BEERS

The purchase of central station power by coal operators for use in and about the coal mines, appears paradoxical owing to the apparent cheapness of fuel at the mines, yet some companies have found it economical to do so, and up to the present time these companies do not regret making contracts for the purchase of power. One large coal company in the anthracite field has closed a contract with a large central station for a long term of years, and with considerable advantage to itself.

To correctly understand the reasons why a large producer of anthracite should find it economical to purchase central station power, it is necessary to have a clear understanding of the ordinary steam production, and the uses to which it is applied in and around the various collieries.

About eight or ten years ago, the writer was discussing with the mechanical engineer of a coal company the seemingly large amounts of steam used in various collieries, as the cry of the colliery people was constantly for more steam, although the installation of new steam consuming devices was in no way proportional to the constantly increasing amount of steam generated.

The mechanical engineer in reply advised that it was simply a waste of money to install more boiler capacity, and made the remark that the surest and best method of increasing the boiler plant capacity was to get busy with the pumps and engines, meaning that if the pumps and engines were kept in suitable repair, or rejected, and an entire new outfit substituted, that the existing boiler plants would be largely in excess of the actual steaming capacity required, and would operate with better load factors with a consequent reduction in steam expense.

A statement of this kind, coming from a liberal minded engineer, is the pure unadulterated truth.

There are old-fashioned pumps in the mines today working on 24-hour service that vary in age from 40 years down, and as long as they are able to push water they apparently fill the bill regardless of the fact that they can digest easily 160 lb. (72.5 kg.) of steam per water horse power. Pumps on long duty service are seldom touched on account of the time necessary to make suitable repairs, and when repairs are made the question is not "how economically will the pump operate," but rather "how short a time will it take to make repairs." One can imagine in what condition the cylinders, pistons, valves, etc., are in, and with tight packing and a poor water end it is not a hard problem to guess where the steam goes.

The same is true of engines. There are fine specimens of old time workmanship and material in service 8760 hours per year. Fans usually must be kept running at any cost, and owing to the inability to shut down the engines to make necessary repairs, the pistons, rings, and valves become badly worn with the result that large quantities of steam are used with a remarkably bad distribution. More than one fan engine shows 90 lb. (40.8 kg.) of steam per indicated horse power. These statements are advanced to show the condition of much of the machinery in use today. Colliery operations are usually conducted with the idea of getting maximum coal output, and little attention or money is spent in keeping the machinery in repair so that it may work at maximum economy.

A great source of loss in the present colliery steam plants today is in the boilers themselves. This is due to the fact that the firemen employed are not very intelligent and their wages are not particularly high. The result is that while fuel is comparatively cheap, little effort is made to use it economically; oftentimes the grates are ill-adapted for the kind of fuel used and this is due to the fact that the fuel varies largely in quality from time to time. Draft arrangements are not always suitable, with the result that much energy goes up the stack. The boiler units are usually small in size, working at large overloads, and no arrangements are made to have them operate at their highest efficiency.

As far as the boiler losses are concerned they are subject to easy control, and one large operating company has made great strides in this direction by expending intelligent effort on the type of boiler used, the grates employed, and the quality of fuel burned.

Long steam lines poorly designed are responsible for much waste of steam. Leaks are seldom repaired, and owing to exposed locations the pipe covering is usually in bad condition.

From the above rough sketch of average conditions it is seen that large steam consumptions are invited, and it is a conservative statement to say that for every effective horse power-hour used in and about the coal mines, 25 to 30 lb. (11.3 to 13.6 kg.) of fuel are burned under the boilers.

During the last eight years the average value of the fuel used under colliery boilers has increased in value from 35 cents per ton to 75 cents per ton and it is still advancing.

Today, an ordinary boiler plant of 700 to 1000 horse power rated capacity has a steam cost of approximately 15 cents per 1000 lb. (453.5 kg.) of steam generated. This figure drops to about 12 cents per 1000 lb. in plants of 2000 to 3000 boiler horse power capacity.

The constantly increasing cost of steam is a condition that the operator is beginning to appreciate, and as a result he is looking for a cheaper form of power. The large savings introduced by the original small electric haulage plants proved suggestive, and as a result many collieries today are electrically operated in whole or in part.

The correct design of a modern central station plant for colliery operations is a rather difficult task, and it requires that the future of the mining operations be clearly forecast. This is an exceedingly difficult thing to do, and as a result, the tendency is to curtail the initial expense as much as possible owing to the uncertainty of future developments. Hence the plant is started on a more or less limited basis with the idea of expansion.

This is good practise, and the engineer being eager to show good economy installs apparatus that permits of a good load factor on the plant, and as a result shows low cost of power at the switchboard. As soon as the plant is loaded, additional apparatus must be installed. The station then will operate at a reduced load factor for some time, although there has been no reduction in the steaming expense; hence the cost per kw-hr. delivered to the switchboard has naturally increased.

This method produces a variation in the kilowatt-hour cost from time to time and may result in the ultimate installation of five or six machines in the plant. Idle time periods and idle hours during the working day require that some machines work at under-load and this with full steam capacity on the boilers, hence the load factor naturally decreases, and as a result the

average kilowatt-hour cost is fairly high. This condition must be so since the boiler plant does not show a proportionate decrease in cost of steam as the load falls off. The continued acquisition of generating capacity along these lines ultimately results in a high cost per kilowatt installed.

The cost per kilowatt installed varies somewhat for each particular case and for a mining central station of two 500-kv-a. turbo-generator units the cost per kilowatt installed was found to be $110.07. This included a 100 deg. superheater for each boiler unit (1200 boiler-horse power was divided into three 400-horse power units). Stokers were also included. The plant operation was based on a 50 per cent load factor. The following is an estimated tabular statement of the fixed charges per kilowatt installed:

Item	Installation cost per kw.	Fixed charges per yr. per kw. Installed
5 per cent int. on station cost	110.07	5.50
10 " " dep. and repairs on machinery	37.70	3.77
5 " " " " " " switchboard	3.00	.15
10 " " " " " " light arrester	.30	.03
10 " " " " " " superheater	4.80	.48
5 " " " " " " bldgs.	6.00	.30
10 " " " " " " coal and ash handling devices	5.00	.50
5 " " " on boilers	42.00	2.10
Boiler repairs (800 h.p. at $2.25 per yr.)		1.80
50 per cent dep. and repairs on condenser (mine water)	3.20	1.60
5 per cent dep. and repairs on steam piping	2.00	.10
10 " " " " " " feed water heater	1.50	.15
2 " " taxes and insurance on plant cost	110.07	2.20
Superintendence, etc.		.32
Total		$19.00

On a basis of 50 per cent load factor we would have the following operating cost per year per kilowatt:

Fuel at 75 cents per ton	7.62
Boiler room attendants	3.42
Power house "	2.00
One general electrician one-half time	0.75
Oil, waste, etc.	0.20
Water	2.12
	$16.11

From these figures it will be observed that there is a constant fixed charge of $19.00 per kilowatt installed which is a constant, regardless of the load on the plant. On a basis of 50 per cent load factor there is a yearly charge estimated at $16.11.

At this point in the argument it is well to consider these values. Under the item of fixed cost the values of depreciation and repairs may be considered high. This is not the case. It must be remembered that the plant is installed as a mining plant to suit mining conditions, and not a main central station in some city. The care exercised in preserving efficiency, etc., is in proportion to the intelligence of the help employed, hence the plant may be considered to depreciate rapidly for two reasons: First, variations in the proposed life of the plant or additions may be required from time to time, with the result that present capacities may be hardly operated before the necessary additions are made, thus bringing about a condition of hard usage; second, obsolesence of equipment. The first reason naturally carries with it large repairs. For these reasons the above values are considered fair, and hence the fixed charge per kilowatt of $19.00 is considered fair.

The operating cost such as coal, water, labor, etc., are the real bones of contention, and at best, their estimate is simply a guess, and the nearer the load factor approaches unity the better the guess. It is at this point, the real crucial point in the kilowatt-hour cost, that many fail, simply because of the high value of the load factor assumed.

The investigation of a mine load shows that on account of hoisting, locomotive, and other variable power service, the load naturally varies largely in a plant of the above rating. The variable load being such as to cause the generators to be temporarily overloaded many times during the day. Also, for many periods during the day they are run at underloads, and neither condition tends toward the best economy, although the load factor based on the kilowatt-hours generated may be fairly high. The result is that a large portion of the kilowatt-hours developed are on ascending parts of the water rate curves of the prime movers, and hence, we approach a condition of good load factor on a reduced steam economy. It is such conditions as these that cause the ordinary mine central station to differ from the regular city central station in which the load varies at uniform rates.

Another condition that tends to destroy the calculated load

factor is the idle day periods, and, when pumping must be taken care of, the absence of large quantities of water. It is estimated that 105 days per year are idle days, and naturally on these days the load factor is not nearly so good as on the regular working day, and particularly is this true if pumping is not required during a part of this time. The fixed charge of $19.00 still keeps on working silently and so does a large portion of the $16.11 due to operating expenses. The only items of this charge that show any real decrease are the coal and water. Therefore, we see that while it is possible to estimate the average kilowatt cost per year at a total of $35.00 or $0.008 per kilowatt-hour on a basis of 50 per cent load factor, there are other things at work that are apt to change this figure considerably.

It will be observed in the original estimate of $110.07 per kilowatt installed that no reserve or emergency equipment has been included. If such had been the case, then the fixed charge of $19.00 would have to be considerably increased, with a resulting increase in the estimated kilowatt-hour cost.

A number of calculations on mine power plants up to and including 1500 kw. capacity resulted in a close agreement of all the figures which may be expressed in concrete form as follows:

Cost per kilowatt installed	$110.07
Fixed charges per kilowatt per year	19.00
Operating charges per kilowatt per year	16.11
Net cost per kilowatt-hour at switchboard	.008
Load factor	50%

A careful study of these statements by the engineer will bring to mind the following questions: "Why must I be saddled with a fixed charge of $19.00 per kw," and "how can I improve the load factor within safe station limits and reduce the kilowatt-hour cost?"

Some years ago a large central station of 40,000-kw. ultimate capacity, located in a mining region, endeavored to interest the company by which I am employed, in central station power, but lack of understanding of mining conditions on the part of the central station always interfered.

Finally it became apparent if the power company could be induced to sell to the mining company at a rate not exceeding eight mills per kw-hr. on a 50 per cent load factor basis, that the proposition would be a fine solution to the above perplexing

questions, and it was with this idea in view that the mining company ultimately took up the consideration of central station power in earnest.

A close study of colliery conditions, such as the expected load factor, periods of high and light loads, peak loads, etc., indicated that if a complete understanding of conditions could be made clear to the power company a contract advantageous to all parties concerned would be considered.

Later a contract was executed to the satisfaction of all concerned, in which the charge per kilowatt-hour was based on load factor only.

Before the contract was signed the following points were taken up and thoroughly discussed:

A. On what basis current would be paid for.

B. Territory to be covered by the contract.

C. Location of meters for registering the power consumed.

D. Delivered voltage, power, and point of delivery.

E. Maximum demand charges.

F. What apparatus should be considered as "connected" load and the methods of rating the same?

G. The included rating of apparatus used intermittently.

H. The method of determining load factor.

K. Pole line charges—co-party lines.

L. Power factor.

M. Explanation of terms used.

O. What constitutes a substation.

The discussion of each of the above topics brought out the following arguments for their adoption, and at the same time illustrates the items that should be considered in any contract between a central station and a mine operator.

A. Current could be paid for either on the "straight maximum demand basis plus cost per kilowatt-hour," or on a varying rate depending on the load factor. The latter plan was argued and adopted, because it is a simpler method of handling all charges. It eliminates errors due to wrong reading of graphic meters, and hence prevents argument as to the demand. To the ordinary mind, it presents the idea of cheaper rates in a clearer manner than rates based on the demand system, as the only point to be observed is that the greater the load factor the less the rate; whereas the straight demand system has a tendency to curtail consumption due to the fact that the demand power may at times be cumulative, and hence the operator may feel worried

as he sees the increase on his demand chart, although his kilowatt-hours may not increase.

B. The contract to be of benefit should be made to cover all territory that a private mining plant could ultimately cover in order that maximum results in load factor would be obtained.

C. The preferred location for meters should be on the secondary side of transformers. This is not absolutely necessary if the central station installed the meters.

In any event they should always be located in the customers' substation.

D. In this case the power company agreed to deliver direct into the customer's substation, consequently it seemed fair and equitable to permit the power company to deliver the power and voltage from its nearest available lines. This particular power delivery should always be specified by letter for any particular substation; experience has proven this to be satisfactory. If the customer was required to build his line into his own substation then he should have the privilege of determining his own voltage in order to suit his delivery requirements. This would eliminate the cost of probable transformers on the part of the customer in lieu of the investment required by the pole line.

E. Under (A) it was decided to use a sliding rate per kilowatt-hour rather than a charge based on maximum demand. On what would the maximum demand be based? Certainly not on the momentary maximum starting loads of motors, as the starting peaks of motors would scarcely be noticed on the load curve of a station of 40,000 kv-a.; neither could a two- or three-minute peak be used on account of the difficulty of properly analyzing curves for such a time limit, as errors would naturally be introduced by the thickness of the line; neither could a five-minute peak be used, because this would tend to eliminate hoisting and this would be unfair to the central station, as much hoisting is done on a one-, two-, or three-minute basis.

To settle this question, the central power plant officials visited many plants in the mining regions, and found from actual observation that the rating of the "connected" load was just about twice the average maximum demand that occurs on the plant. Experience proved this to be fairly close, hence for the term "maximum demand" a figure was used that was equal to one-half of the total "connected" load, rated in kilowatts.

F. Since the basis of cost was load factor and since the "max-

imum demand" as outlined above is used in lieu of station capacity it is necessay to correctly define the "connected load."

This to consist of all direct power consuming devices (no transformers, converters, motor-generator sets, etc.) and is equal to the sum of the name plate ratings of all motors, or lamps, or heating devices, etc.

Exceptions. D-c. hoist and d-c. locomotives to be rated on one hour nominal rated basis. A-c. hoists to be rated on their continuous basis, and where transformers are used for lighting only, then the full kilowatt rating of the transformers is used.

G. Suppose reserve equipment should be installed such as pumps to give protection in time of floods. This equipment would be in service only a few weeks total time per year. It was considered equitable to include this apparatus only for the month during which it was used. It is reasonable to state that in a private mining plant emergency conditions are given preference, and therefore other apparatus would not be worked; for this reason it was considered that such reserve equipment should not be carried from month to month as connected load.

H. The method of determining load factors was intimated in (F) and is as follows: Let the total manufacturers name plate rating of apparatus used during the month equal 500 kw. and let the total kilowatt-hours used during the month of thirty days equal 72,000; then the maximum demand is equal to 500 divided by 2, equals 250, and the average demand is equal to 72,000 divided by 30 days times 24, equals 100; therefore, 100 divided by 250 equals 40 per cent which is the load factor. Reference to the cost curve shows the rate to be approximately $.009, therefore the charge for that particular month would be 72,000 kw-hr. times $.009 equals $648.00.

K. If the coal company should require the power company to build a power line expressly to reach a substation, then it seems fair and equitable that the power company should be paid a charge on this line that will represent a total investment charge on the line. However, if the coal company uses power of a value in excess of this investment charge, then no pole line cost shall be included in the monthly bill, but if no power is used then the full investment charge is to be paid. This service was fixed at 15 per cent of the pole line cost.

Exceptions. If the power company should place extra customers on this line, then this 15 per cent line charge should be pro-rated among the various customers in proportion to their respective "demands."

L. At all times it is to the interest of the coal company to have the proper voltage. The installation of considerable amounts of induction machinery tends to destroy this feature, and may cause trouble to pumps, fans, and hoists, hence to protect itself it is good policy on the part of the coal company to use power factor correcting devices judiciously.

M. In order that no errors in calculations in load factors, etc. could arise through ignorance, the power company considered it advisable to make use of definitions that clearly explain the following terms:

Maximum demand.

Manufacturers name plate rating.

Load factor.

Day.

O. To suitably define the word "substation" it was determined that all operations that could be conveniently grouped under one colliery lease should be known as a substation.

From the above discussion of the elements of a power contract it is seen how essential it is that the central station people should be made to thoroughly understand colliery operations and the conditions relating to connected loads, and in addition they should be made to appreciate the fact that the day load is highly desirable as it reduces their station losses and increases their load factor to a very high degree, and when the night loads occur that they are usually of the constant duty kind.

Failures on the part of others to obtain satisfactory rates could no doubt be charged directly to this lack of knowledge on the part of the central station which is due to the failure of the mining company to properly co-operate with the central station people.

The company with which I am connected has been operating on central station power for about one year, and up to the present we have about 1000 kw. connected load consisting of fans, pumps, hoists, locomotives, and heaters, and provisions are being made to increase this amount in the near future by about 2500 kw. Plans are now under way to remove the present boiler plant from a colliery and operate entirely by central station power.

Since operating on central station power, a number of features have presented themselves that make it look like a very satisfactory arrangement. They are as follows:

1. Our average kilowatt cost is lower than the estimated kilowatt charges in the ratio of about 7½ to 8, and this kilowatt

charge is based on delivery at our substation meters, and not at the main power house switchboard as per the original data.

2. The company is more ready to consider additions to its power equipment due to the fact that main power plant costs have been entirely eliminated and do not appear in the estimate.

3. There is always a "readiness to serve" on the part of the central station and this is seldom true of the mining power plant.

4. There is absolutely no worry due to power plant operation.

5. In case of holidays etc. the monthly bill will increase slightly, which would not be the case in those plants operated by the mining company for in such plants labor and fuel decrease but little.

6. As electric operations increase, less demands are made on the colliery boiler plant with the result that coal will be sent to a ready market which otherwise would be burned under the boilers, and ultimately this will be no small amount of fuel.

7. The use of central station power affords a remarkably cheap method of reaching isolated banks, and isolated pumping problems. Operations such as small washeries are more or less temporary in character, and can be advantageously worked without causing the distress that might be occasioned when operated from a mine central station.

8. The service is reliable. Our service up to the present time does not total more than 15 minutes delay due to failure of supply and these failures were directly due to lightning.

9. The effect of efficiency is not particularly noticeable hence air gaps can be made larger which is highly desirable in mining apparatus as it reduces the danger of break-down.

In the above discussion the author has presented the case of mine central station, vs. public service corporation supply as it appears to him. Experience has been somewhat limited, but the longer the service is continued the more is the author convinced that the purchase of power from public service corporations offers advantages that should not be overlooked by mining corporations.

DISCUSSION ON "PURCHASED POWER IN COAL MINES" (EDDY) AND "CENTRAL STATION POWER FOR COAL MINES" (BEERS), PITTSBURGH, PA., APRIL 18, 1913.

K. A. Pauly: We are very fortunate to have secured these valuable papers on this very important subject of central station versus isolated plants for coal mines. Many of the points brought out might readily form the subjects for separate papers. Such papers are especially valuable because they give the views of engineers, who, because of their experience, are eminently competent to deal with the subject. I do wish, however, to point out and emphasize the agreement between these three engineers whose opinions are based on actual and independent experiences, representing both sides of the question. While there are doubtless large mining companies which can and do maintain highly efficient and economical electric generating and distributing systems, it appears to me to be a foregone conclusion that in general—and this is especially true of all but the larger companies—a public service corporation should be in a position to deliver power at a lower cost than it can be produced in an isolated plant and that, in addition, the service should be much more reliable.

We have, on the one hand, a mining company whose efforts are devoted to the production of coal at a minimum cost, and in which cost the item of power plays but a minor part. In addition to this the power cost is handicapped by a low load factor, resulting in high fixed charges and operating costs, which combine to give a high power cost. On the other hand, the one object of the public service corporation is that of developing cheap and reliable power. It maintains a corps of competent engineers who devote their entire time to the problems incident to the development of cheap and reliable service. They have at their command the necessary capital to introduce improvements and make extensions, which make for lower power cost. Assisting them in their efforts, they have the greatest diversity of loads to bring up their load factor. To sum it up, so to speak, the one is a coal manufacturer and the other a manufacturer of power.

There is but one detail to which I wish to refer in connection with these papers, and that is the question of steam and fuel consumption brought out in Mr. Beers' paper. The contention made by the advocates of the isolated plant, as has been pointed out, is that the price of coal is low. Fuel is but one of the items entering into the cost of power, and the low priced fuel is not necessarily the most economical to use. These inferior grades are high in ash content, require more labor in the boiler plant, and cause a considerably higher cost for maintaining the boilers which may nearly, if not quite, offset the low cost per ton for fuel. I am especially interested in Mr. Beers' statements with regard to the steam and coal consumption of the present, in

many cases, obsolete steam equipments about the mines. We advocates of the application of electricity to mining operations have always contended that the actual steam consumptions are far in excess of the figures given by our steam competitors, but never before have we had so complete and positive a statement of the facts as is given in Mr. Beers' paper. Much of this inefficiency is due to wear with age. Contrast with this the almost constant efficiency with the electric motor, which varies but slightly with length of time in service. Again, a great deal of the high fuel consumption is chargeable directly to the low load factor, under which the small isolated plants are operating. I am familiar with a seven day test of a large mine hoist which gave approximately seventy-five pounds of steam per shaft horse-power-hour as the water rate of the engine, and showed that the fuel consumed during the idle period of the hoist was approximately 50 per cent of that required for hoisting.

George H. Morse: Mr. Eddy has remarked that the power plant of the mine is by natural causes necessarily located at the least advantageous point, that is, at the mouth of the mine. Those are natural causes of disadvantage. I recently installed a fan plant in Eastern Ohio, which suffered from difficulties which came through artificial causes. I refer to the recent law passed in Ohio limiting the voltage to 250 volts in the mines. Two hundred and fifty volts may do for some mines, but there are other mines, which are of sufficient length to make it necessary to use 500 volts, if power is to be transmitted from the mouth of the mine to the interior of the mine. I have in mind one mine at Wheeling in which they have for several years used 220 volts. The mine has gone on increasing in length, and the next step was to introduce a booster, because the voltage was low and the motors heated, and now the booster is not sufficient, and at the mouth of the mine, there are perhaps a dozen large cables, of 600,000 cir. mils waiting to reinforce the copper. These conditions notwithstanding, the point I wish to emphasize is this, that the position taken by the legislature in Ohio, in permitting even 250 volts to be used in mines, is, in my opinion, wrong. Two hundred and fifty volts is, to the speaker's thinking, too high. In fact, if we could have the power introduced into suitable points in the mine at high and workable voltage, so far as primary is concerned, and then reduce it even to as low as 50 volts, I think that insulation troubles and death from electric causes would be very much reduced.

E. D. Dreyfus: The various papers that exemplify the advantages of "importing" power to the coal mine add another chapter to "exploded" theories. On first thought one would naturally suppose that coal as it was disemboweled from the earth could be most economically converted into power on the spot for use on the premises. But this now has been generally proven to fall far short of reality owing to the modifying and

militating conditions which have been discussed. The ideas held by our forebears likewise conflict with the present developments, as is evident in referring to the saying originated by an English writer by the name of Fuller, in 1661, "To carry coals to New Castle" (the Pittsburgh coal district of Great Britain), which was used as an expression of a preposterous situation. This conception is no longer valid since we see on every hand power companies delivering the energy equivalent of the coal to the very heart of the mine at distances that already greatly exceed 50 miles. The evolution curiously does not stop at this point, for we are beginning to witness a gradual substitution of the "black diamond" for producing the power required in coal mining by a much more valuable resource in the nature of "white coal" or water power.

The march of progress in this direction has been very marked. In rather limited time, I have personally observed over 200 coal mining companies that have become users of central station power, and this I know is a small percentage of the whole, and the rapidity with which new mines are added to the lists seems to be mostly a factor of time in which the power companies find themselves able to extend their service to the scattered locations. The coal mine operator through his lengthy experience in the production and utilization of coal intuitively becomes a very capable judge of the unit value of power, which often makes "fine haired" figuring unnecessary with him. If ideal cost only were considered the increased use of purchased power by the coal mines would have been impeded, but the practical sense of the operator has fortunately prevailed. I mention these facts merely to indicate that we must go cautiously into the subject of general cost of power. To do it justice we will have to cover an almost limitless field. There are more variable factors and intangibles in power costs than many of us are able to appreciate, and to broadly compare rates, prices or cost without a definite accounting of conditions would be entirely improper. In the philosophy of power costs there must be a liberal reckoning with the various elements that go to make up the total expense. And by virtue of these conditions no two installations or situations in any two districts are directly comparable.

The Pittsburgh district has evidently been the pioneer in this country in applying central station power to the coal mine on a large and extensive scale, and other territories have been able undoubtedly to profit by the important development wrought in this region. But the economy of production has in the meantime advanced to such a degree that the tonnage costs under similar circumstances would be lower than in other localities even if they were to pay higher prices in some cases. However, on examination, and with load factor and surroundings balanced, it is believed that it will be found that the Pittsburgh district enjoys very excellent rates which correspondingly are at the

lowest possible level when favorable operations either obtain or are assumed.

Finally we should regard the character of the mine electrical equipment as carefully as the cost and reliability of the central station supply. I can not urge too strongly the employment of the best talent in planning and executing the local installation. Central stations invariably prefer to serve mines in which the application of electrical equipment is properly made, rather than where the apparatus and methods are inefficient, although the amount of power consumed is greater in the latter case. They desire that the service be entirely satisfactory in every respect even if it results in a smaller income to them. Some of the good work that has been carried out under the supervision of our professional electrical engineers has been prominently reflected in the success and economy of the mines for which they have stood responsible.

T. E. Tynes: As to the points enumerated in Mr. Beers' paper, I fail to see any mention made as to whether the coal operator is reimbursed for interruptions to his service, incurred by the power company.

W. Partridge: I would like to call attention to Mr. Beers' figures in which he apparently shows that power can be produced for 8 mills. This may be true in Mr. Beers' case, with a comparatively large station of about 1000 kv-a., and with 85 and 50 per cent load factors, but in the mine plants with which we have had experience the load factor is nearer 20 per cent. Also most of the mining operators are willing to charge for their coal the price which they can get for it on the cars, which would be, at least $1. If you do a little figuring, changing the load factor, and changing the coal, you will, in small plants of 100, 200 or 300 h.p., get a cost in the neighborhood of 2 cents per kw-hr. Recently in Boston I ran across an engineer accustomed to install small plants in mills and factories. His ideas and mine on the subject of power costs were entirely different. He started out by saying that he thought it was absurd to think that at a coal mine, power could be bought from the central station cheaper than it could be manufactured, and then he asked what our rates were. I told him in the case under consideration the rate would be somewhere around 1.5 cents per kw-hr. He thought that that was too low, and that any company that was willing to make a contract to supply power for 1.5 c. per kw-hr., should be required to give a bond to the company with which the contract was made, for fear that the power company might wind up at any minute. Then afterward he got out his pencil and started to figure what he could make the power for, and before he got through he had it down to ¾ ct. per kw-hr., including the fixed charges for a little plant of about 200 h.p. He did not like to figure on a kw-hr. basis. His figures were on the h.p. basis, and one of his claims was that he could and was producing power in a number of plants in New

England on 1.5 lb. of coal per h.p-hr. I afterwards came to the conclusion that one of the ways in which he was fooling himself and his customers, was this. He would take an engine installation, of say, 300 h.p., and take the total cost of operating the engine for 10 hours a day throughout the month, and then assume that the engine was carrying full load during the entire period. Such a basis is easily exploded by taking indicator diagrams on the engine, and those who are familar with selling power on a kw-hr. basis know that the load factor on almost any type of machinery is generally nearer 20, 30 or 40 per cent than it is 100 per cent.

W. E. Dickinson: Practically everything has been said on the side of central stations that can be said, and I have nothing to add, but for the sake of argument I want to call attention to a few points that may suggest a debate here. I should like some one to take sides against the central station to open a debate, knowing the popularity of the central station in connection with coal mining operations.

Mr. Beers in his paper brought out the fact that much steam was used around the coal mine anyway. So, I ask, has he charged up in the fixed charges the expenses of that part of the steam plant used purely and distinctly and entirely for the electrical side of his power plant, or has he charged in repairs and depreciation, etc., for that part of the boiler equipment that is to be used generally for other purposes?

He has brought out the fact that power generated today at 8 mills has been satisfactory. I should like to know what central station company will sell power at 8 mills. I should be glad if any one here, who is willing to make a contract to sell power at 8 mills, for a fairly long period, will let me know where I can see him to arrange for the purchase of power on that basis, as I should like to jot it down for future reference. If you begin to bargain with a central station power plant for power, they are more apt to charge about 2 cents or 3 cents, than 8 mills or 8.5 mills. To purchase power at 8 mills is certainly unusual.

Mr. Beers spoke of it being only fair to pay 15 per cent on the first cost of the pole line. Has he added that into the cost of his power?

Then, his definition of the substation is rather a complex one. He speaks of the substation as being at any prearranged point in one colliery, for instance, at the entrance thereto; while Mr. Eddy speaks of the advantages of the central station because of the ability to move the motor-generator set from one point to another, and the probability of being able to duplicate motor-generator sets and of placing them at several points. I ask whether the attendants upon the motor-generator set or the synchronous converter would not make an additional cost to the coal company? Neither speaker seems to have considered this expense.

Now, another point that has been suggested as favoring the use of central station power is changing the feeding point. Would not that also be possible in using a local power plant, and would not that also entail additional cost?

The making of a long term contract may be beneficial to the coal company, but it may be detrimental to the coal company, under certain conditions, because of the fact that the long term contract is binding upon either company. If, in any way, the coal company should find it to its advantage to make some change in its equipment, it is bound down by a long term contract. The time may come when the erection of its own central station may be justified by the extension of its property.

I believe that those are about the only points I noticed especially that might be brought up for argument.

H. C. Eddy: Various companies that are incorporated under the title "American Gas & Electric Company" are entirely willing to sell power under certain conditions at 8 mills, or even slightly under 8 mills. The cost of producing that power is easily all of that, or perhaps more, and it might be a pertinent question to ask how we can make money by selling power at less than it costs to produce. The answer to that is very simple, it is composed of two words: Diversity factor.

You have an output in a certain given plant of a certain number of kw-hr. per month or per year, which costs to produce at the switchboard a certain amount, suppose we say it costs 8 mills to produce it. That, under ordinary conditions of load, means a comparatively low plant load factor for twenty-four hours, and it is the twenty-four hours' expense that is the most important. The result is that if we can find a customer who will use our facilities and our capacity and our investment, during those hours in the twenty-four when the majority of our customers do not use these things, we can afford very well to sell that power during those hours at about the cost of production, and make a profit, because it will reduce our total cost per kw-hr. for all that we turn out.

There was one other point that the gentleman brought out, and that was the matter of the change of location of motor-generator sets. He suggested that that might be equally feasible in the case of an individual mine power plant. It is, provided the individual mine power plant has the necessary equipment to transmit current for considerable distances with slight loss; in other words if the plant is equipped with alternating-current generators and can deliver current at anywhere from 2300 volts upwards, they can install motor-generator sets, with synchronous converters, and move them about with the same facility as though they were purchasing power, but the fact remains that there are only one or two coal mining companies that do busines on that basis. They are very large, and they have that sort of equipment. The average coal mine, however, has one or two 150-kw. generators, 220 or 500 volts. Occasionally you will find a mine that

has a generator of 300 kw. capacity in one size, or something of that kind, but in this section of the country, with the bituminous mines, at least, they run to small units as a rule.

The result is that if they were to sacrifice the present equipment and replace it with the proper amount of alternating-current apparatus, and then were to go further and buy the necessary conversion equipment, their plant cost would continue to go up, and their fixed charges would be correspondingly higher, and their cost per kw. hr. would be increased, so that, even under those circumstances, it would be cheaper for them to limit their investment to the conversion apparatus only, and then place it where it will do the most good.

George R. Wood: I think Mr. Eddy underrates the average size and number of central station mining plants. There are today between 15 and 20 a-c. mining plants with substations, and I believe the average d-c. plant is 300 kw. or over.

There is one additional advantage in purchased power, compared with your own d-c. plant. In the latter case, as the mine advances and requirements increase, an addition to generating capacity means an investment of $80 to $100 per kw. With purchased power, only an additional substation is required, with investment of $15 to $20 per kw.

C. W. Beers: In regard to the power company paying the coal company for delays, I want to say that there is a penalty clause in our contract with the power company from which we purchase power, and under which they are responsible for delays. They agree to pay our company a certain sum of money, to be reached by agreement, for any delays that occur which are serious enough to interrupt the operations of the mining company. We also have in that contract a clause which gives the power company the right to ask us for delays or interruptions, without charge. For instance, they may want to do something to their generator plant, and we could afford to shut down, say, from some period on Sunday until some later period on Sunday evening, or from Saturday evening until Sunday morning, or something of that kind, so that we are advised in advance to make these arrangements; but for unexpected delays in our operations, resulting from the power company failing to give us power, and which result in damage to us, the power company will pay us a certain sum of money.

In regard to the question of bringing up the case of cost of steam in electrically operated plants, we have no steam at those collieries that we propose to operate electrically. We may bring up the question of heating at these particular plants, but we have not got up to the point yet where we are really running any boiler plant for heating purposes at all. So far we have confined ourselves to a small test, that we are now conducting, in regard to heating by stoves or heating by electric power. We have not come to any particular conclusion on that point, but at one big colliery, that we are proposing to operate entirely

by electricity, we will probably during the cold winter months run a small boiler plant.

With reference to the question as to what power company sells power for 8 mills, in the case of the power company I am buying from, we are paying monthly bills now as low as 5.3 mills per kw.

In regard to the question of pole line cost, whether or not we have included this in our annual costs, I want to say we have not included any pole line costs so far, because as soon as we get a line in we propose to load that line up. We want to keep above the minimum charge. We think that is our privilege to do. Where we do not use power, we pay the 15 per cent, but we do not propose to have a line go in and not use it. We expect to use every line and to load it up.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

SAFEGUARDING THE USE OF ELECTRICITY IN MINES

BY H. H. CLARK

In connection with the use of electricity in mining work there are three possible dangers—shocks, fires and explosions. The electrical accidents that occur most frequently are shocks. The conditions under ground are peculiarly favorable to the occurrence of such accidents. One can scarcely imagine conditions that are more conducive to the occurrence of electric shocks than the intimate association of bare conductors with many more or less untrained men standing upon the ground, or upon track rails, in limited spaces that are damp, dusty and poorly lighted.

Sources of Electric Shocks

Trolley wires in mines present the most fruitful sources of electric shocks. Trolley wires are necessarily bare conductors that extend for long distances throughout a mine. They are often installed less than a man's height above the track rail that is used as part of the return circuit, and they are often installed in this manner in places where men must work in making up trips (trains) of cars, as, for instance, at points where loaded trips are brought by electric locomotives to the foot of a rope haulage system.

Another source of danger from electric shock is the accidental charging of parts of equipment that are not supposed to carry electric current. Shocks of this character are obtained most frequently from the frames of coal-cutting machines. The frames of locomotives become charged to the same potential as the trolley wire, if, while the motor or headlights are in operation, the locomotive loses its ground by reason of oversanding

or for any other cause. Under such circumstances a very severe shock can be obtained between the locomotive frame and the ground.

Fires Caused by Electricity

The danger from fires caused by electricity arises principally from defective installation and careless up-keep, or from injuries to equipment resulting from falls of roof or similar causes. A short circuit or ground that does not blow the circuit breaker or the fuses may produce heat enough to start a fire by leaking across coal or timbering. The blowing of an open fuse may be accompanied by sufficient heat to ignite combustible material that is close to the fuse. The presence of inflammable material around electric motors or starting rheostats may prove to be a source of trouble. Incandescent lamps produce heat enough to ignite combustible material if the dissipation of heat from the bulbs of such lamps is allowed to become restricted.

Explosions Caused by Electricity

Explosions may be caused by the ingition of explosives, mine gas or coal dust. Accidents due to the ignition of explosives by electricity may be divided into two classes—those that occur while handling and transporting explosives near electric circuits and those that are incident to the detonation of explosives by electrical means.

As to accidents of the first class (with a single exception mentioned hereafter) electricity is no more of a menace than any other source of flame or heat, but it is just as great a menace and should be treated accordingly. As much care should be used in handling explosives in the vicinity of electrical apparatus as though the flashes and sparks that it is capable of giving were constantly in evidence.

Any source of heat may attack an explosive from the outside, but electricity may, under certain conditions, do more than that. An explosive that is a conductor of electricity may come in contact with an electric circuit in such a way that current may be passed through the explosive itself, and although no spark may occur outside the package containing the explosive ignition may take place on the inside. The possibility of such an occurrence may seem to be extremely remote, but accidents have been reported for which no other cause could be assigned, and in which the existence of the above conditions was quite probable.

Since the drawbars of mine cars are electrically connected throughout the length of the trip it follows that whenever the locomotive loses its ground all the drawbars are raised to the potential of the trolley wire, unless some of the drawbars are in contact with the car axles or some of their connections. If the drawbars of a car loaded with metallic packages of explosives were raised to the trolley wire potential it can be easily imagined that the bolts of the car axles could become connected to the drawbar in such a way that the current would flow through the packages and possibly through the explosive itself.

The accidents that occur in connection with electrical shot firing are largely due to the accidental discharge of detonators in the vicinity of explosives, or to the premature ignition of shots after the holes are charged.

With regard to the accidental discharge of detonators in the vicinity of explosives; it is a cardinal principle of safety that detonators should be kept separate from explosives, and that batteries and other sources of electric energy should be kept separate from detonators.

With regard to the premature ignition of shots; it is not the best practise to shoot electrically under conditions that require one side of the detonating circuit to be connected to the earth, because wherever grounded systems of distribution are used, unexpected differences of potential exist in the earth in the vicinity of such circuits. If, therefore, one side of the detonator be purposely grounded, an accidental ground on the other side of the detonator may connect it across a potential sufficient to cause ignition. Premature ignitions have been reported which seemingly have been caused by the conditions just described.

Electric sparks will ignite mine gas and air mixtures that contain between 5.5 and 12.5 per cent of gas (methane). Between these limits (which are rather widely separated) a comparatively small spark is sufficient to ignite the gaseous mixture. For all practical purposes it is safest to assume that all sparks that occur around such electrical apparatus and circuits, as are used for power and lighting in a mine, are capable of igniting gas.

The study of the ignition of coal dust by electric arcs and electric flashes has been undertaken and carried on to some extent by European investigators. The results of their experiments indicate that electric flashes can ignite coal dust suspended in the atmosphere. The Bureau of Mines is now at work upon a similar investigation, which has not, however, progressed far enough to permit of the publication of results.

Conditions Surrounding Electrical Installations in Mines

Underground electrical installations are surrounded by many more trouble-causing factors than are met with above ground. Falls of roof sufficient to wreck trolley lines and feeder systems are of frequent occurrence. Dampness, dust and acid water in sufficient quantities to be detrimental to insulation are not uncommon. Some or all of these conditions must usually be considered in selecting mine electrical equipment. Apparatus that might operate satisfactorily in the absence of these elements will fail when they are present. The space available for installing and operating underground electrical equipment is usually limited, thus increasing the chances for accidental contact with the live parts of the electrical system. Another factor that will appeal especially to those not accustomed to underground work is the lack of light. Not only has this condition a direct bearing upon the accidental contact with the electrical apparatus, but it also has an undesirable indirect influence, because of the difficulties that it places in the way of property installing and inspecting equipment.

As compared with electrical installations above ground, those underground are temporary in character. Circuits and machines are put in place with the certain knowledge that sooner or later they must be removed and installed elsewhere. There is also a good deal of portable apparatus used, such as portable pumps, coal-cutting machines and drills. It is, therefore clear that the economical investment in installation is limited to a far greater extent than it would be upon the surface where equipment is usually permanently installed. This condition increases the natural difficulties of maintaining underground electrical equipment in a condition that is absolutely safe, but it has often occurred to the writer that one of the factors that has been most influential in delaying improvement in underground electrical conditions is the fact that the electrical dangers contribute only a small percentage to the annual death rate in mines. As an illustration; statistics show that less than 3 per cent of the men killed in and about the coal mines of the United States during the first eight months of the year 1912 met their death as the result of electrical causes. It is not that the number of men annually killed in mines by electricity is not undesirably great, but that the number of men killed underground by other causes is so much greater that it quite overshadows the electrical death

roll. If the thirty-seven men who were killed by electricity in and about the coal mines of the United States during the first eight months of 1912 had been the only ones killed in connection with the mining industry, effective measures to improve the electrical conditions underground would no doubt have been taken immediately.

Prevention of Accidents Caused by Electricity

The problem of safeguarding electric mine equipment is not a simple one, and at first glance involves so many considerations as to appear hopelessly confusing. A logical first step in improvement of underground conditions would be to remove or to counteract as many unfavorable conditions as may be thus disposed of. As previously stated, scanty light, limited space, and the presence of dust and dampness are underground conditions that are favorable to the occurrence of electrical accidents. The influence of the first of these may be eliminated by providing lights at particularly dangerous places, such as partings and cross-overs. If electric wires are a source of danger at such places they can also be made a source of light to reduce that danger. Although it may be impracticable to eliminate entirely the effect of limited space, this condition may be counteracted by the erection of guards about apparatus. Dust and dampness are elements that can hardly be separated from the operation of a mine; in fact the presence of dampness is often desirable to offset the effect of dust. It is possible, however, to provide apparatus so designed and installed as to resist the action of dust and dampness and the more generous the factor of safety included in such design and installation the greater will be its resistance to undesirable influences.

The problem of safeguarding may be divested of some of its vagueness and put in concrete form by considering that if the electric current can be kept where it belongs—in the conductors designed to carry it—it can not give shocks, set fires, or ignite gas, dust or explosives. Electricity becomes actively dangerous only when it breaks away from its proper channels in stray currents or as sparks and arcs. So far as stray currents are concerned, the confinement of electricity in its proper place is primarily a question of insulation, a term that includes the covering of conductors, the insulators upon which they are supported, and the insulating material used in motors and accessory equipment.

It is sometimes argued that the insulating coverings of conductors deteriorate so rapidly that they provide an added element of danger, because they give a false impression of safety. This argument can not be regarded as universally applicable because its truth depends upon the kind of insulation used and the conditions of service. If bare conductors are used, they should be well installed and to some extent at least guarded, in order to confine the current. With the possible exception of high voltage cables, all conductors, bare or insulated, should be supported upon insulators that are mechanically strong as well as electrically efficient. If bare conductors are used, confinement of the current depends entirely upon the insulators. Moreover, dampness and dust can come into direct contact with the wire, a condition not consistent with the highest factor of safety.

In order to insure a high factor of safety in the insulation of motors and other electrical machines, they must be carefully selected with a view to the service that they are to perform. They must then be protected from moisture and dust, unless such protection is inherent in their design. Care in this respect will be rewarded not only by increased safety, but also by decreased cost of up-keep.

It must be admitted that the electric current can not be kept where it belongs in the sense of eliminating entirely such sparks and arcs as occur at fuses, circuit breakers, air-break switches, starting rheostats, and the commutators of direct-current machines. In this connection the factor of safty must be applied by arranging to confine the outbursts of current to a limited area unoccupied by anything that may be affected by heat or fire.

Assuming that in the installation and insulation of electrical equipment care has been exercised to insure the proper confinement of the current, the factor of safety may be increased by grounding the dead metallic parts of apparatus, by providing means for insulating the bodies of those who work upon such apparatus, and by barring from the vicinity of the current such elements as are explosive or combustible.

It is as important to maintain a high factor of safety as to obtain it in the first place and such maintenance calls for careful and frequent inspection by the mine electrician, whose responsibility can scarcely be overrated. The supervision of the electrical equipment of a mine is a task that requires unusual ability, sound judgment, and experience of a peculiar sort. To

select suitable apparatus, to install it properly, and to maintain it free from interruption of service at a minimum cost demands ability. The requirements of safety add a further load of responsibility. It seems to the writer that the electrician holds the key to the problem of safeguarding the use of electricity in mining work. The electrician is the man that deals with the problem at the closest range and in the position of greatest advantage to observe dangers, to correct improper conditions, and to maintain a suitable factor of safety. The power to truly and effectively safeguard the use of electricity in mines rests more with him than with any other one man.

By the way of summary there are offered the following suggestions for reducing the number of accidents due to the use of electricity in mines:

1. Remove contributory causes.
2. Remove from the vicinity of electrical apparatus all elements susceptible to its influence (gas, dust, explosives, combustible material, etc.).
3. Keep the electric current where it belongs.
4. If, under certain circumstances, the current cannot be entirely confined, at least limit the area of its activity by using protective devices.
5. Insure a high factor of safety by (a) selecting material and apparatus with care, (b) installing equipment in a strictly first class manner, (c) inspecting equipment frequently and thoroughly, (d) maintaining it in good condition at all times.

Electrical Equipment that Promotes Safety

In the foregoing, electricity has been discussed as a menace to life and property. There are, however, some ways in which it seems possible for electricity to decrease the risks now attendant upon mining work. There is one piece of electrical equipment that may almost be considered as a safety device and there are three others that by substitution for more dangerous equipment and methods promote the safety of underground workers.

First may be mentioned the telephone, which is of use in spreading the news of trouble, in calling aid to the injured, and in assisting in mine rescue work after disasters. Next may be mentioned portable electric lamps for use of miners. The development of such lamps is just beginning in the United States. At the date of this writing no device has been fully developed and standardized for insuring absolute freedom from gas ignition

by lamps of this sort. There can be no doubt, however, that in the near future some such device will be developed and then the electric lamp becomes safer than the locked safety lamp, although it has not the latter's ability to detect the presence of explosive gas. The statement that the electric lamp may be made safer than the safety lamp is based upon the fact that the parts of a safety lamp may be improperly arranged and ignition of gas occur as the result. The records show that this has happened on more than one occasion.

The greatest benefits to be derived from the electric lamp as a safety device will be had in those mines where the electric lamp supplants the open flame lamp and thereby eliminates a real fire hazard.

Next may be mentioned the firing of shots by electrical means. There can be no doubt that the firing of shots by properly designed and operated electrical shot firing devices and equipment, is safer than firing shots by fuses or other devices that ignite explosives by means of sparks or flames.

Finally, it may be suggested that electricity may partially do away with its own greatest danger by substituting storage battery locomotives for gathering locomotives operated from trolley wires. Although main line haulage by storage battery locomotives can hardly be advocated at present, the gathering of coal by storage battery locomotives seems, in many instances, to be a feasible proposition. The use of storage battery locomotives would entirely do away with the trolley wire from a large part of the mine entries that are now provided with this dangerous equipment. In addition to the greater degree of safety assured, storage battery locomotives would be more flexible to operate than are cable reel locomotives. The load factor on the generating station would be materially improved, satisfactory voltage regulation of the distributing system could be obtained with less copper, and the expense of installing and maintaining trolley wire and rail bonding would be eliminated in the entries worked by storage battery locomotives.

DISCUSSION ON "SAFEGUARDING THE USE OF ELECTRICITY IN MINES" (CLARK), PITTSBURG, PA., APRIL 18, 1913.

C. A. Lauffer: During the past four years I have been an advocate of the Schafer prone pressure method. This method bids fair to become the universal method employed for resuscitation. During this time it has been my privilege to instruct over two thousand men in giving artificial respiration, and I have done considerable writing and speaking on the subject of artificial respiration.

But in coming before you today, I came expecting to hear what somebody else was going to say. It did not occur to me that your chairman would call upon me. I presume that every gentleman here has read the report of the National Electric Light Association on the subject of resuscitation. The Committee appointed by that Association, which was composed jointly of prominent engineers, and eminent physicians agreed unanimously that the Schafer method is the most promising method to employ in efforts at resuscitation. When the manufacturers of mechanical devices produce something that every electrical workman can carry round in his vest pocket, then we will agree that the manual method can be supplanted by the mechanical method, but so long as mechanical devices are so large and so difficult to have when they are most needed, if we neglect instruction by manual methods, the present loss of life will continue to be disastrous.

As to the mechanics of artificial respiration by the prone pressure method, we know that in breathing, the main muscle which is used is the diaphragm. The diaphragm is arched, and above the diaphragm lie the lungs and the heart. Below the diaphragm, under these ribs, up to the fifth rib lies the stomach. On the other side lies the liver. Below these organs, behind, lie the two kidneys. Behind the stomach on the left side lies the spleen.

Now, when we give artificial respiration by the prone pressure method, we lay a man on his stomach and turn his head to the side. In turning his head to the side we prevent the mouth making contact with dirt or water. We turn his head to the side, and that permits any fluid in the mouth or air passages to run out. When we lay him on his stomach and turn his head to the side his tongue falls forward. There is no necessity of any device to pull the tongue forward, because gravity causes the tongue to fall forward. With the patient in that position, lying prone, with his arms spread out, or above his head, we proceed to make pressure on the lowest ribs. The pressure is made on the eleventh and twelfth ribs with the heel of the operator's hands, and the pressure is made far out towards the ends of the ribs. When pressure is made that way for three seconds, it is possible to empty the lungs, it is possible to drive out more air than is ordinarily driven out in our natural breathing, so that by making the pressure

twelve times a minute, and completely removing our hands after each pressure, we see at once that we are giving the man more cubic inches of air than he gets in his natural breathing, and we are bringing back into play the diaphragm; we are forcing these movable organs of the abdomen up against the diaphragm in a manner that not only restores the action of the lungs but also assists in maintaining the action of the heart. We cannot give massage of the heart, such as is done sometimes during abdominal operations, manually, but we can give massage of the heart by throwing these movable organs up against the diaphragm twelve times each minute. There have been several instances where victims of electric shock, declared dead by physicians, were brought to by friends of the apparent victims. It very often happens that linemen and electric workmen have better muscles than doctors, and more courage and consequently more success; because, with the people who have the courage, the tenacity of purpose, this prone pressure method succeeds admirably in quite a number of cases.

J. S. Jenks: I will ask the doctor a few questions for the benefit of some of us here concerning the length of time it would be advisable to keep up such action, and the advisability of the use of stimulants, and methods of administering them, and methods of aiding and assisting the heart and lung action by hypodermics or some such thing as gases of different kinds, or the reëstablishing of breathing by slight electric shock.

I have given this matter considerable thought, and have tried to instruct and train our men in the manner in which they would be able to take care of their comrades in case of accident, and have supplied them with small cases containing hypodermics, atropin, nitro-glycerin, strychnin, etc., and gave instructions where they could procure such gases as would be advisable and advantageous in producing results in extreme cases.

Now, the thing that has impressed me—I have been at a number of cases of accidental shock—is the fact that everybody gets excited, that they go to work with a vim, and work at high speed, and do not take the time that is necessary. I want to emphasize that point of the time element. I have tried to tell our boys and instruct them to count three slowly after each operation, and if they do not do that, they get all worked up, and do not see results, and tire themselves out readily, and give up, and I believe many a good man dies just on account of a man's over-exertion in the early part of the attempt at resuscitation.

I would like Dr. Lauffer to elaborate on the time a man should continue to work. I have known of several cases where there was complete resuscitation after periods of one and three-quarter hours of continuous and unceasing efforts by fellow workmen and physicians and attendants. I have also known of cases where we had very extreme cases of burning and apparent death, and the victim was brought around in as short a time as three minutes through the aid of some stimulation.

C. A. Lauffer: The best gas to inhale is aromatic spirits of ammonia. That is readily available. If you do not have aromatic spirits of ammonia, use any kind of ammonia. If you use aromatic spirits of ammonia, the handkerchief can be saturated and held about three inches from the nose. If you use household ammonia, and it is full strength, try it on your own nose first—dilute it with water, or hold it farther away—and do not take an unfair advantage of an unconscious man. Then as to oxygen, I think aromatic spirits of ammonia is superior, provided you are in the fresh air. In the case of mine gases and various chemical combinations, it seems to me that oxygen, under certain circumstances, is superior to fresh air and ammonia.

No liquid should be poured into the mouth of an unconscious man.

Now, as to hypodermic medication, we never instruct the men to give that themselves. There is usually a doctor available, and the hypodermic drugs have to be administered with much care. The best drug is atropin, the second best drug is strychnin, and when you are not getting results, you give both; both right away, and as soon afterwards as you can, it is a good plan to give digitalin, cactin and camphor in oil, and then other hypodermic stimulants, such as the physician may have with him.

As to the amount of stimulation which you can give, that is a question which ought to be left with the physician. To a certain extent you can whip a mule and make it go, but after a while the mule will drop dead, and it is the same way in the matter of stimulating the heart. To a certain extent you want to stimulate but beyond that too many doses of strychnin are going to prove fatal.

I took no notes of your questions, and consequently I may miss some of them. There was a question asked as to the duration of the treatment. I have known results to be delayed for two or three hours, and in some cases I have seen results come within less than twenty minutes. I know of one case in particular where everybody thought that the man was dead. He was a man about fifty-seven years of age; he had fallen nine feet, lighting on the concrete floor, with his whole weight, on the back of his head, and he was a heavy man. He had a marked case of concussion, and was unconscious; he had no respiration or pulse, and with the stethoscope you could not hear his heart. His comrades knew about artificial respiration and kept busy, and my assistant reached the man and worked over him, giving him artificial respiration; and then he started to breathe and soon stopped again, and as soon as he would stop they would start again, and by keeping him on his stomach and giving artificial respiration by this method, in about one hour's time he came to sufficiently to vomit, and from that time was able to breathe normally. Under ordinary circumstances a man who sustains a fall on his head, or a man who gets a blow in his solar plexus, is going to die, because there is no one around who knows how

to give artificial respiration; the general public must take up the subject of artificial respiration and learn how to give it, for you cannot expect doctors endeavoring to reach the scene, always to arrive in time. These people must be assisted. If a man has not breathed in two minutes, he is in as great danger as a man who has been without food for forty days.

Ralph D. Mershon: I noted the pressure you exerted was long-continued and slow, and I judge that is an important feature of the treatment.

C. A. Lauffer: That is the best way, begin the pressure gradually, and continue it until you feel the ribs give way under your hand. Some people are much firmer in their ribs and in their costal cartilages than others; and occasionally you run across a conscious man in these exercises who will exert all the force he has to prevent your giving him the artificial respiration, but when the patient allows himself to be perfectly passive, you will find that a few pounds of pressure will be ample. You can apply the pressure gently, gradually increasing, and when you have reached the limit of compression, then suddenly remove your hands. As you remove your hands, those organs which you have displaced upward by the pressure will drop down again; the diaphragm will descend and the air will rush in. As you make the pressure you raise the diaphragm and compress the lungs and drive out the air. As soon as you remove your hands, these organs fall back into their former places.

The question has been asked if there is any danger of breaking the ribs. I think not. I have never heard of it happening. I suppose if you put enough weight on you can do it, but the blows which break ribs are sudden blows. A man does not break ribs from lifting, and he does not have his ribs broken from such a gradual, firm pressure on his ribs. The only person who can experience any damage by the prone pressure method of treatment is somebody with cancer of the stomach or liver, or a far-advanced case of tuberculosis, but the people who are a living pathological museum are not the men who are engaged in the active pursuits of life.

George R. Wood: I would emphasize that for the purpose of the mining men, we can almost disregard the matter of hypodermics and the other administration of medicine. What the mining man should do is to send for a doctor and then start artificial respiration, and let the company doctor do the other things.

Graham Bright: Mr. Clark brings up the question of sand on the track insulating the locomotive and causing current to go back through the cars and create trouble. This is a point which has caused a great deal of contention between the manufacturers and the operators in that the operator sometimes wants a locomotive that is too light. The result of a light locomotive is that he has to pile sand on the track to get the cars up the grade, causing a great deal of dusty grit to work its way into the

bearings. It would be very much to the advantage of the operator if he would either obtain a locomotive large enough, or cut the trips down, so that he does not need the abundant use of sand. Aside from this damage, and the damage or trouble mentioned by Mr. Clark, another trouble exists, in that you provide a sand path for the cars to run on, which, of course, increases the rolling friction of the locomotive and cars, and you also cut down the available voltage for the locomotive by increasing the electrical resistance between the wheels and track. As brought out in Mr. Eddy's paper, low voltage is the cause of a great many of the troubles that take place in mine locomotives and is the cause of much of the high upkeep, owing to the windings of the motors burning out.

Another point Mr. Clark has brought out is the question of storage battery locomotives for mine service. Any one who has had very much to do with storage batteries knows that they require rather expert attendance, and we can well imagine what will happen to the average storage battery that does not receive any more attention than the average mine locomotive gets. In the first place, many of you who have been in mines have no doubt noticed that a considerable number of the locomotives will have their side or end frames cracked or broken, showing that in mines as well as railways on the surface, we have not yet solved the problem of two locomotives running in opposite directions on the same track. You can imagine what would happen to the ordinary storage battery in one of these collisions, so that if we are going to go to storage batteries, we must select one which is mechanically strong and will stand these collisions which are liable to occur in the best regulated mine.

Another point about these storage battery locomotives is that there is a tendency among some of the smaller manufacturers to build a locomotive which they can offer for a very low price. The locomotive must necessarily be of light construction, which makes it totally inadequate to meet the severe conditions about a mine. If we are going to build a storage battery locomotive it must be amply strong to stand the rough usage incident to the mine service, and a locomotive to withstand that service cannot be obtained in the case of many of the storage battery locomotives in industrial service at present. Industrial service is generally outside in the open, or in well-lighted buildings, and the chance of collision is very small. They can get a better class of operators, because industrial plants are, as a rule, located in large industrial centers where the living is much better and it is a comparatively easy matter to get a good class of men to take care of these locomotives, so while the storage battery locomotive sounds like a good way out of some of our difficulties, in the way of protection from electrical trouble, there are a good many details to be worked out, before it can be made a successful gathering locomotive.

W. E. Dickinson: There is one subject that Mr. Clark treated in his paper that is of special interest to me, viz., the accidenta

discharge of shots after the charge has been made. As most of you know, this matter was investigated to a certain extent in Kentucky, and it was thought to have been demonstrated that stray currents have fired shots when copper needles were used. I believe that it was stated that within a mine investigated, considerable electrical potential existed between certain points, sufficient, it was decided, to produce in the explosive a current sufficient to ignite the shot.

I do not understand how such a conclusion could have been drawn. It is an easy matter to find with a sensitive voltmeter a potential difference between two points in a mine. But it is difficult to get an appreciable current to flow through even an ammeter connected to these two points, owing to the internal resistance of the circuit through which the current must flow. Moreover, the explosives used in shot firing are of very high electrical resistance. Admitting that the current may travel through the copper needle, it must then find its way through the explosive and be large enough to generate therein sufficient heat to fire the shot. It is quite doubtful that even stray currents leaking from trolley to track would select the high resistance path of the explosive material. But it is very probable that leakage currents will enter poorly insulated detonator leads under favorable conditions and thus prematurely discharge a shot.

Mr. Clark said, however, that if currents are held within their proper channels by proper insulation, it is not possible for them to ignite shots. I can not entirely agree with him on this point. I believe that many accidents in mines are due to induced currents in short circuits, regardless of the nature of the insulation of the power lines.

Some time ago my attention was called to an accident which occurred in West Virginia, in which a shot was fired prematurely when a hand generator was to be used. The leads from the detonator had been untwisted and brought out separately into an adjacent passage. The generator was then placed between the rails of the motor track and connected to the detonator leads. When all preparations had been made as usual, the operator attempted to fire, the shot failed; another attempt to discharge the generator was made without success. The man was about to investigate the trouble when the shot went off unexpectedly. Fortunately, he was not seriously injured, and lived to describe the conditions.

There was a motor operating on the track, and you know that a motor in starting up will draw an immense current for a short time. This current sets up a rapidly changing magnetic field around the track and trolley. And such a field of flux, when favorably cutting a closed conductor of low resistance, may induce in a circuit a voltage sufficient to produce a current large enough to fire a shot. So, it occurred to me that a premature discharge of a detonator might be attributed to induced currents under favorable conditions. I do not know that this was the

specific cause in the case described, but I could not attribute the accident to leakage currents occasioned by poor insulation. I feel sure, however, that under certain conditions it is possible for such an accident to occur. If a pair of untwisted wires are run from a detonator, for even a short distance, along a rail carrying a varying current, and one wire is on one side of the rail and the other wire on the opposite side, or one wire is close to the rail and the other located at considerable distance therefrom, the circuit being completed by the generator, no insulation would prevent the induction of current sufficient to fire an electric cap in the circuit. I need not go further into the technicalities of this point. But I wish to add that immunity from such a danger lies in the use of leads well twisted from battery to detonator. And this is a precaution to which we seldom pay sufficient attention.

Wilfred Sykes: I would like to draw attention to one point in Mr. Clark's paper, where he says: "If the 37 men who were killed by electricity in and about the coal mines of the United States during the first eight months of 1912 had been the only ones killed in connection with the mining industry, effective measures to improve the electrical conditions underground would no doubt have been taken immediately." I want to draw attention to the increasing attention that is now being given to the question of safety. Our steel mills at one time killed great numbers of men. In the last few years the people running the mills have come to the conclusion it is not very economical, and to protect their own interests they have given the question of safety a great deal of attention and spent a great deal of money upon it.

It seems to me that the number of accidents can be materially reduced by the work of the Bureau of Mines, if it obtains proper statistics and analyzes the causes of these accidents. The same thing is being done in other industries, and in this connection I wish to say—I am not quite sure of my figures—that about four or five years ago the number of accidents in steel mills in this country per ton of product was several times greater than they were in Europe, particularly in Germany. I understand at the present time, through the campaign which has been carried on, particularly by the electrical engineers, who have assumed the duties of safety engineers, that the number of accidents has been reduced until we have less accidents per ton of material produced than in Europe.

I think that the work of the Bureau of Mines, in which Mr. Clark has taken an active part, can materially reduce the number of accidents, by the collection of statistics, and by having proper regulations adopted in the different states. Perhaps, in that connection, we may some day see federal regulations controlling the mining industry, and then we will have a much better control over electrical work.

L. R. Palmer: May I ask Mr. Clark what is the method of testing the electric safety lamp as compared with the standard

safety lamp, and how you can determine their relative merits in that line?

The last speaker mentioned the work done by the electrical engineers in the line of safety. Perhaps it might be well to present to the Chairman of this meeting the report of the First Co-operative Safety Congress, held at Milwaukee, Wisconsin, September 30 to October 5, 1912, under the auspices of the Association of Iron and Steel Electrical Engineers, with headquarters at the Hotel Pfister. It was an electrical engineer who first suggested that this Congress be held, and it was Mr. Gano Dunn who was our chief adviser and assisted in drawing up the resolutions that brought into being the National Council for Industrial Safety. Anybody who cares to see a copy of that report can get it by writing to any member of the committee which was appointed to manage the affairs of the Congress.

George R. Wood: Referring to electrical accidents mentioned by Mr. Clark, the tendency is to magnify electrical accidents on account of the comparative novelty of electrical mining, and to lose sight of the general improvement in mining conditions, and reduction of the general hazard by its use.

For example, in 1911, Pennsylvania State Reports show 265 fatal accidents to 66,000 pick miners, or 4 per 1000. There were 127 fatal accidents to 55,000 machine runners, loaders and scrapers, or 1.3 per 1000. Had Pennsylvania's total output been mined by hand, total number of pick miners would be 136,000, with, on the same ratio, 544 fatal accidents, against 392 at present.

The same reasoning applies to haulage, where one locomotive, with two men, replaces 5 to 20 mules, each with a driver.

The increased output per man employed, resulting from the installation of electrical machinery, results also in decreased liability to accident, on account of the reduction in number of men employed.

Almost every mining district in the country today is short of men, and it would be impossible to operate in a large proportion of the bituminous districts without the use of electrical machines, locomotives and pumps.

Harold H. Clark: Mr. Bright spoke rather discouragingly of the use of storage battery locomotives. It was far from my intention to suggest that everybody should at once adopt the storage battery locomotive even for gathering, but I think it undoubtedly would be a step towards safety, and as such I mentioned it. I will further say that I believe that one of these days a practical storage battery locomotive will be developed for gathering.

Mr. Bright's remarks concerning the necessary staunchness of the construction of such a locomotive are well considered. Such a locomotive, and the batteries used to operate it, must be very strong, and very simple to operate. There are storage batteries, I believe, for which strong claims are made along these lines.

Mr. Dickinson spoke of the stray currents, and spoke of the possibility of detonators being discharged by induction in the leads from heavy currents in the rail. I do not consider this to be impossible, but at first glance it would seem rather improbable.

In regard to what Mr. Sykes says about collecting, classifying, and publishing the accidents that occur underground: That is something that is now done by the State Inspection Departments and published every year, usually about a year after the close of the annual period in which the accidents occurred.

The Bureau of Mines several months ago published Technical Paper No. 27, the title of which is "Monthly Statement of Coal Mine Accidents in the United States, January to August, 1912, with statistics for 1910 and 1911."

Mr. Palmer asked about the electric safety lamp test. In the Bureau's Technical Paper No. 47, just received from the printer, are given the characteristics of portable electric lamps as compared to flame safety lamps.

Schedule No. 5 just issued by the Bureau outlines conditions under which the Bureau will test electric lamps to determine their permissibility for use in gaseous mines. These conditions call for a high standard of design and construction. The electric lamp is so safe anyway, that any device applied to it to make it safer must be very nearly, if not quite, 100 per cent efficient, and the tests that we are going to make on those lamps are based on the fact that they should be nearly perfect. We shall take these lamps and try in every way possible to make them ignite gas, and then if we pass them, we shall be reasonably sure they are perfectly safe for use in any mine, no matter how gaseous. Experiments that are reported in Technical Paper 47 seem to indicate that sparks that may come from storage batteries up to a 3-cell battery, or 6 volts, will not ignite mine gas. If such a battery were short-circuited a spark that would ignite gas might be produced if the short-circuit current of the battery were rather larger than the ordinary battery would give, something like 100 amperes for a 2-volt cell and 85 amperes for a 4-volt cell. The only danger that the Bureau believes to exist in connection with portable electric lamps is the ignition of gas by the glowing filament of the lamp, and prescribes that such lamps shall be provided with safety devices, so that if the bulb should be broken, the circuit will be broken, or the lamp short-circuited, so that the carbon filament will not glow at a temperature sufficient to ignite gas.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

ALTERNATING-CURRENT MOTORS FOR THE ECONOMIC OPERATION OF MINE FANS

BY F. B. CROSBY

It is no longer necessary for the advocate of electric drive to dwell at length upon its many advantages. The superior qualities of the electric motor are thoroughly attested by its all but universal adoption in every industrial field requiring the application of mechanical power at widely separated or otherwise inaccessible points. The question which confronts the engineer today, save in exceptional instances, is not that of relative merits of the several possible methods of transmitting energy to the point of application, but rather it is a question of the intelligent selection of the most suitable electrical equipment with due consideration of all factors bearing upon the particular case in hand.

Efficient motor design is essentially a compromise. No single type possesses all the desirable characteristics of the ideal machine. Recognizing the limitation of design and the physical impossibility of producing a universal motor, electrical manufacturers are giving more and more attention to the specific requirements of certain clearly defined classes of service. As a result of this specialization and the steadily increasing variety of forms manufactured, it is obviously of greatest importance that for any given duty the proper motor be selected, otherwise a motor which under conditions for which it is designed, would give entire satisfaction, may very likely under different conditions prove an utter failure or at best a needlessly expensive piece of apparatus. For example, induction motors can be readily designed to develop at reduced speeds:

a. Constant horse power, —increasing torque.
b. Constant torque,—horse power proportional to speed.
c. Torque decreasing with speed.

Moreover these motors can be given either a maximum or overload rating. The power required to drive a centrifugal mine fan varies approximately as the cube of the speed. Obviously to install for fan service a motor capable of developing constant horse power at reduced speeds or with any considerable overload capacity, does not represent sound engineering, either from the standpoint of first costs or operating characteristics.

It is the purpose of this paper to indicate certain considerations which should govern the selection of the mine fan motor and describe briefly those types which have been adapted to this service. No attempt is made to discuss the relative merits of the several types of fan on the market or forced draft as compared with the suction draft fan. It is assumed that the type of fan and horsepower required to operate it have been determined for any given application.

Two general conditions arise requiring (1) constant speed drive, and (2) adjustable speed drive. Until recently, for adjustable speed drives, it was practically necessary to install direct-current motors. This necessity no longer exists. In laying out new installations not handicapped by an existing direct-current system, alternating-current motors only need be considered.

In the following discussion the term "constant speed" implies no appreciable change of speed from no-load to full-load; "variable speed" implies speeds varying with the load, but constant at constant load; "adjustable speed" implies several independent speeds, each constant under varying load. In either case the polyphase alternating current motor in some one of its several forms fully meets all requirements. The advantages of alternating current from the standpoint of efficient transmission and facility of manipulation are well recognized, as are also the high efficiency, sturdiness, simplicity of operation and low maintenance charges of the induction motor.

I. Constant-Speed Drive

This is obviously the simplest condition met with and is found chiefly in connection with long railway tunnels, subways, and old mine workings in which the volume and pressure of air handled is practically constant twenty-four hours a day and every day in the year. For such service the standard polyphase induc-

tion motor is without a competitor. Properly installed, such a motor can be stopped or started automatically in emergency by remote control and will run constantly without attention other than occasional inspection of the oiling system. Whether the squirrel cage or phase wound rotor should be used depends upon the capacity of the generating and transmission systems and the maximum permissible peak loads during starting. The question of voltage depends upon location and capacity of the motor. It is rarely advisable to carry more than 220 or 440 volts underground. For motors of 300 h. p. or less, above ground, it is in general desirable to use 2300 volts, or less, although 6600 volts can be used for motors as small as 150 h.p. with slight sacrifice of power factor. If high voltage must be used for transmission to remote points, the cost of a low voltage motor with suitable step-down transformers will usually be about the same as for the high voltage motor, while the operating characteristics of the former will be somewhat better.

II. Adjustable-Speed Drives

The great majority of mine fan installations require an adjustable-speed drive and for this reason, as stated above, until comparatively recently it has been practically necessary to install direct-current motors with shunt speed characteristics.

Good ventilation is fundamentally essential in all underground mining operations. Not only must the temperature and the carbon dioxid (CO_2) content be kept down for most efficient working conditions but also especially in coal mines poisonous and explosive gases, such as carbon monoxid or "fire damp" (CO) and the scarcely less dangerous inflammable coal dust suspended in the air, must be continuously removed. Absolute continuity of service and reliability under all conditions are imperative requirements of fan service.

It is evident that in contrast with the conditions outlined in case I, the volume and pressure which the fan must deliver increases from day to day as the headings are advanced and the drifts extended. To accomplish this the speed of the fan must be increased from time to time until the limit of efficient operation is reached. It has become standard practise to install a fan of sufficient capacity to meet the ultimate requirements at maximum speed and operate it at reduced speed when first installed. Such a fan may be operated six or eight months or a year at the minimum speed and light loads before the first increase in speed

is required. It is frequently years before the maximum capacity is required.

The average fan motor operates under practically constant load throughout long periods, consequently maximum efficiency is a consideration secondary only to the reliability of operation. The direct current shunt motor shows a fairly high efficiency throughout its range of operating speeds but its installation is subject to the disadvantages of the first cost, maintenance, and attendance inherent in a direct-current generating and distributing system. As compared with these disadvantages the many desirable characteristics of the induction motor have frequently led to its installation even at the cost of a compromise between efficiency and desirable operating speeds. Numerous schemes for obtaining speed control for polyphase induction motors have been developed. Among those of chief importance are the following:

1. Constant-speed motors with changeable pulleys.
2. Variable-speed motors with rheostatic control.
3. Multi-speed windings.
4. Concatenation.
5. Single cascade motors.
6. Dynamic regulation.
7. Brush shifting motors.

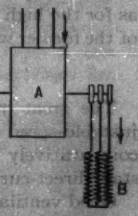


FIG. 1—INDUCTION MOTOR AND RHEOSTATIC CONTROL.

1. *Changing pulleys* is obviously a makeshift method subject to annoying delays and limitations such as practical ratio of pulley diameters, and distance between center lines of shafts, etc.

2. *Rheostatic Control.* When operated with negligible secondary resistance the polyphase induction motor is inherently a constant speed machine. Continuous speed control can be had by means of an adjustable resistance in the secondary circuit but the efficiency falls rapidly as the range of operating speeds is increased. (Fig. 4). In Fig. 1, *A* is the main motor and *B* is the external secondary resistance. Assuming that 50 per cent speed reduction by rheostatic control is required, it follows that the shaft output, with fan load must be approximately $(\frac{1}{2})^3 = 12.5$ per cent, and an equal amount of energy must be dissipated in the rheostat in addition to the losses in the motor itself. The effect on overall efficiency is obvious.

Another vital objection to rheostatic control lies in the fact

that with external resistance in the secondary circuit, the speed varies with the load, accelerating under light loads and dropping again, to a value determined by the secondary resistance when the load comes on. Since at no-load the secondary current is negligible, no amount of resistance within reasonable limits will hold down the speed of the motor.

Fig. 2 shows increase in speed of motor corresponding to several initial speeds when load is changed from $1\frac{1}{4}$ to $\frac{1}{4}$ times full load torque.

3. *Multi-Speed Windings.* Where two definite constant

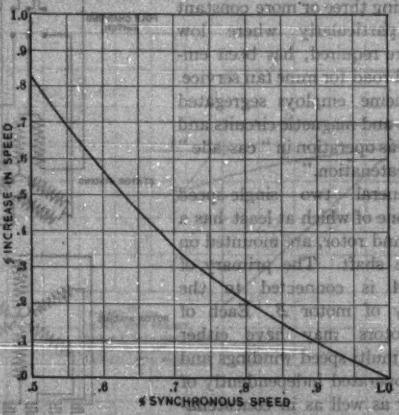


FIG. 2—INCREASED SPEED CORRESPONDING TO DECREASED TORQUE.

speeds are sufficient the induction motor can often be supplied with external connections by means of which the polar grouping can readily be changed to give the desired synchronous speeds. The cost of such a motor is but slightly more than that of a single speed motor provided a 2:1 ratio is employed for the high and low speeds. Where a ratio other than 2:1, or where three or four constant speeds are required, the condition can sometimes be effectively met by two separate windings in the same slots, one or both of these windings being arranged for external multi-polar grouping. Three separate windings are not permissible in practical design. Such motors are sometimes used with or without

changeable pulleys and rheostatic control for intermediate speeds, but at best are a compromise, since the number of constant speed steps is limited by characteristics of design and by prohibitive costs. Rheostatic control is always objectionable for reasons noted above.

Fig. 3 shows diagrammatically the arrangement of stator and rotor windings for a two-speed changeable pole motor.

Fig. 4 shows typical efficiency and power factor curves for a two-speed motor with rheostatic control.

4. *Concatenation.* Another method of obtaining three or more constant speeds, particularly where low speeds are required, has been employed abroad for mine fan service. This scheme employs segregated electrical and magnetic circuits and is known as operation in "cascade" or "concatenation."

In general two single-speed motors, one of which at least has a polar wound rotor, are mounted on the same shaft. The primary of motor *A* is connected to the secondary of motor *B*. Each of these motors may have either single or multi-speed windings and may be operated independently of the other as well as in concatenation. The second motor may have either a phase-wound or squirrel-cage rotor. In case phase-wound rotors are used, speed regulation by secondary rheostatic control may be obtained in the usual manner, and with the usual objections.

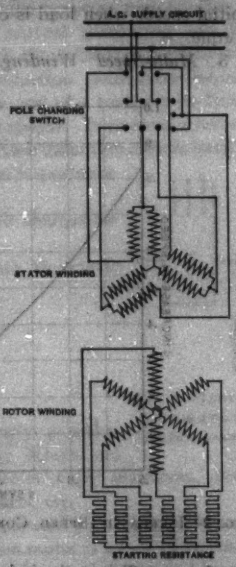


FIG. 3—MULTI-SPEED MOTOR WINDINGS

Two motors are connected in direct concatenation if they show a tendency to start in the same direction and in differential concatenation if they tend to start in opposite directions. The synchronous speed of motors in concatenation may be determined as follows:

$$\text{Speed} = \frac{\text{cycles} \times 120}{P_1 \pm P_2}$$

where P_1 = number of poles of first motor and P_2 = the number of poles of the second motor, the plus sign being used for direct and the minus for differential concatenation.

With the multi-speed pole changing motors it is necessary to open the primary circuit when changing from one speed to the other, this may be avoided in concatenated sets by introducing resistance in the leads between the two motors, the resistance being cut in or out step by step when changing speeds. (Fig. 5).

As noted with a polar-wound rotor, any reduction in speed by

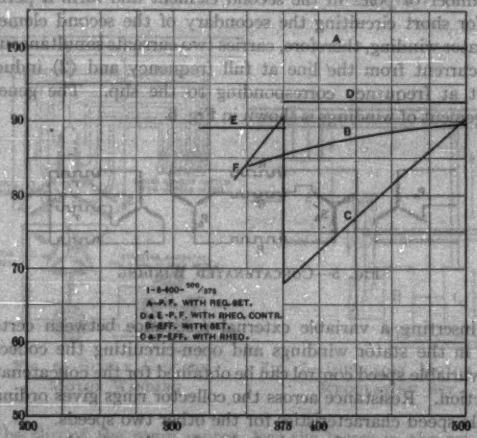


FIG. 4—EFFICIENCY AND POWER FACTOR, TWO-SPEED CONSTANT HORSE POWER INDUCTION MOTOR

rheostatic control is accompanied by a proportionate reduction in efficiency, the power factor remaining practically constant. With concatenated motors the efficiency remains approximately constant provided there is no external resistance in the rotor circuit of the second motor, while, at the lower speed, the power factor drops, due to the fact that as compared with their normal individual ratings, the motors are underloaded when in concatenation.

5. *Single Cascade Motor.* The single cascade motor offers still another method of obtaining two or three definite fixed

speeds. This motor has an internally concatenated winding. The stator winding is of the usual full and half speed type. The single winding of the rotor is so arranged that its magnetizing effect is the same as would be produced by two separate windings. It is, however, a decided improvement over two separate windings, since all coils which in such cases would neutralize each other are omitted in the concatenated connection and grouped together for connection to the slip rings for use only at other speeds. When the primary of the first element is properly connected with two circuits per phase in multiple corresponding to the number of poles, these circuits are in exact opposition for the number of poles in the second element and form a perfect path for short circuiting the secondary of the second element. The stator winding, therefore, carries two currents simultaneously (1) a current from the line at full frequency and (2) induced current at frequency corresponding to the slip. The general arrangement of windings is shown in Fig. 6.

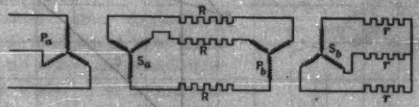


FIG. 5—CONCATENATED WINDING

By inserting a variable external resistance between certain points in the stator windings and open-circuiting the collector rings, variable speed control can be obtained for the concatenated connection. Resistance across the collector rings gives ordinary variable speed characteristics for the other two speeds.

This type of motor is particularly adapted to the three speeds corresponding to the polar ratios 1-2 and 3, for example 4-8-12, 6-12-18 etc.

6. *Dynamic Regulation.* As stated earlier in this paper each of the foregoing schemes possesses inherent disadvantages which until recently have made it practically necessary to employ a direct current motor with shunt characteristics whenever close regulation was required for a large number of speeds each constant under varying loads.

Recently means have been perfected whereby shunt speed characteristics can be had with the standard polyphase induction motor together with high power factor and high efficiency

throughout the range of operating speeds. The method employed is susceptible of several modifications and will be referred to inclusively as dynamic regulation. With rheostatic control the secondary energy is dissipated as heat whereas with dynamic regulation the major portion of this energy is returned to the system. Referring to Fig. 7, the external resistance *B* of Fig. 1 is replaced by the compensated commutator motor *B*, which forms one element of a two unit motor-generator set, the second element of which is a standard squirrel cage induction motor connected to the supply mains. This machine is driven slightly above synchronism by the commutator motor and operating as an induction generator returns to the system, energy proportional

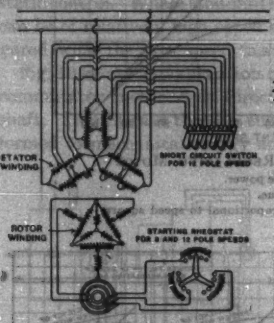


FIG. 6—SINGLE CASCADE MOTOR WINDING

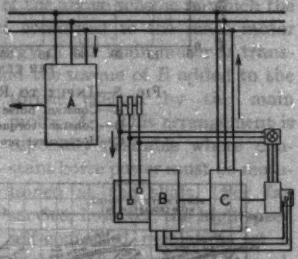


FIG. 7—INDUCTION MOTOR WITH REGULATING SET

to the slip of the main motor, less the losses in the set itself. The commutator motor receives energy from the secondary of the main motor at relatively low frequencies and in general must have a proportionately small percentage of the main motor capacity. Assuming that *A* is to drive a fan at 50 per cent of synchronous speed the horse power delivered to the fan will be approximately 12.5 per cent, of the rated capacity of the motor and the same amount of energy will be delivered to the regulating set.

If the connected load required constant horse power at the motor shaft, then neglecting losses, the motor input at 50 per cent speed would be 200 per cent, the shaft horse power 100 per cent and the energy returned to the system 100 per cent.

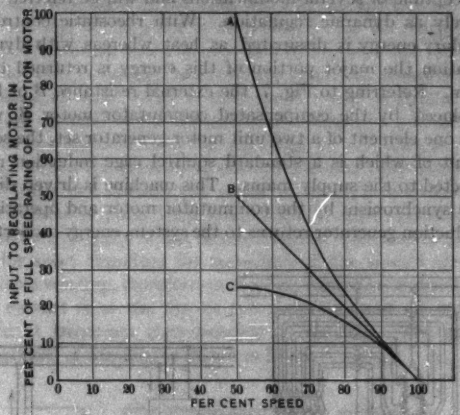


FIG. 8—INPUT TO REGULATING MOTOR

A—Constant horse power.
B—Constant torque.
C—Horsepower proportional to speed square.

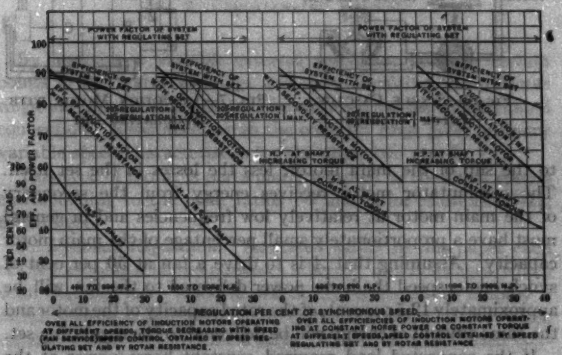


FIG. 9

If again the connected load required constant torque at the motor shaft, then neglecting the losses, the motor input would be 100 per cent, the shaft output 50 per cent, and 50 per cent would be returned to the system. This is shown graphically in Fig. 8. If X per cent regulation is required at constant torque the motor generator set must have X per cent of the normal horsepower capacity of the main motor. In general where the required torque varies with the speed the regulating set must have $\frac{X}{1-X}$ per cent of the normal h.p. capacity of the main motor. Fig. 9 shows typical curves of efficiency and power factor for the conditions indicated above with dynamic regulation and rheostatic control. Where standard regulating sets are employed they can be of relatively high speed and inexpensive design as compared with the slow speed main motor.

Fig. 10 shows a modification of the above scheme in which the commutator motor B is direct connected to the main motor shaft. In this case the slip energy of the main motor is transformed to mechanical energy and the torque of B added to the torque exerted by the main motor A. This arrangement is especially desirable where constant horse power must be maintained at the shaft. For fan service, however, the high-speed self-contained regulating set is usually cheaper and yields equally satisfactory results. Furthermore, the possibility of applying the standard regulating set to any standard induction motor with phase-wound rotor in event of future re-arrangement of equipment, is an important advantage.

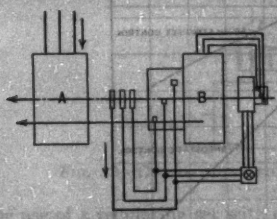


FIG. 10—DIRECT-CONNECTED COMMUTATOR MOTOR

In addition to the advantages of adjustable constant speeds under varying load and high operating efficiency the possibilities of power factor correction are often of great importance. If desired, unity power factor can be maintained on the main motor with all the usual beneficial results in improved regulation and increased energy capacity in power station and transmission system. Unity power factor correction naturally involves a somewhat more expensive set since the magnetizing current is supplied by the commutator motor instead of from the line. The standard sets should have sufficient capacity to raise the power

factor of the main motor about 10 per cent, maintaining an average power factor of 95 per cent or in some cases 100 per cent without increased cost. In special cases it is possible to supply sufficient magnetizing current from the commutator motor to give the main motor a leading power factor thus obtaining a certain corrective effect for low power factor conditions on the external system. The kilovolt-ampere capacity, copper losses and first cost will be increased and the overall efficiency lower in this case.

The operation of the set with magnetic control is very simple. The induction generator is thrown across the line by means of standard compensator and brought up to speed as an ordinary squirrel cage motor. The main motor is started by closing the primary oil switch and accelerated by automatic current limit or

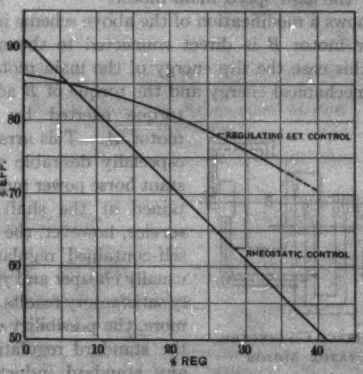


FIG. 11—EFFICIENCIES, 400-H.P. MOTOR

hand control. The speed of the main motor adjusts itself to the tension determined by the setting of the exciter field rheostat. Any further speed adjustment is obtained by the manipulation of this exciter field rheostat.

The range of speed regulation obtained is limited by the maximum frequency impressed on the commutator motor. In general for good design this should not exceed approximately 20 cycles, which will give about 30 per cent regulation on a 60 cycle motor. This limit varies somewhat with the size of motor involved.

This system was developed in Europe and in the past four years about thirty equipments have been put in successful operation for mine fans and rolling mills. Ten similar equipments have been sold in this country within the last six months.

Fig. 11 shows efficiency curves with regulating set and with rheostatic control for a 400-h.p. motor driving a mine fan. Two of these motors were actually installed and operated continuously at 40 per cent speed regulation by rheostatic control for nearly a year. Under these conditions the input to the fan would be 21.6 per cent, and the energy dissipated in the rheostat or delivered to the regulating set 14.4 per cent, of the full load rating of the motor. From the curves the relative overall efficiencies with rheostatic and dynamic control are seen to be 51 per cent and 70.5 per cent respectively. The relative power consumption is therefore 169.5 h.p. and 122.5 h.p. or a net saving of 47.0 horse power per machine. Assuming that power can be purchased for one cent per kw-hr., the net saving due to

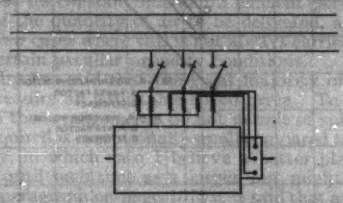


FIG. 12—CONNECTIONS FOR BRUSH SHIFTING MOTOR

the use of a regulating set with each fan 12 hours per day 300 days per year would be $0.01 \times 47.0 \times 0.746 \times 12 \times 300 \times 2 = \$2525.00$ approximately. In many gaseous mines the fans must operate continuously 24 hours per day every day in the year, in which case the above net savings would become $6160.00.

7. *Brush Shifting.* For fan installations requiring motors of 100 h.p. or less capacity, in place of the regulating sets described above, the brush shifting polyphase motor can often be employed to advantage. Fig. 12 indicates the general arrangement of connections for this type of motor. The motor derives its name from the fact that it is started, stopped, reversed and controlled by merely shifting the brushes. With a certain brush setting no torque is developed, consequently the motor will not start when the line switch is closed until the brushes are moved from this position. The speed of the motor is proportional to the shrub

shift. Reverse operation can be obtained by moving the brushes in the opposite direction from the zero position, but for best commutation two phases should also be reversed for reverse operations. Brush shifting is accomplished by means of suitable worm gear and hand wheel conveniently located. Commutation is excellent throughout the entire speed range. Fig. 13, shows power factor and efficiency curves for a 60-h.p. brush shifting motor and for an ordinary induction motor with rheostatic control designed for fan service. These curves were plotted from actual test data.

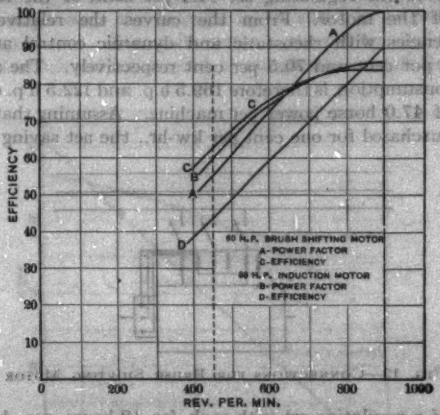


FIG. 13— POWER FACTOR AND EFFICIENCY FOR BRUSH SHIFTING MOTOR

The minimum permissible speed depends largely upon the torque requirements of the driven load. For fan service this type of motor will give stable operation at very low speeds corresponding approximately to 70 per cent slip below synchronism.

In conclusion it would appear to the writer that in the absence of an existing direct-current system, the advantages of the polyphase motor leave small ground for the application of direct-current motors for either constant or adjustable speed fan drive.

DISCUSSION ON "ALTERNATING-CURRENT MOTORS FOR THE ECONOMIC OPERATION OF MINE FANS" (CROSBY), PITTSBURGH, PA., APRIL 18, 1913.

C. W. Beers: The title of Mr. Crosby's paper is apt to convey, to my mind, something misleading. It deals with the motor side of the question and leaves out the fan side of the question, and I would like to give a few points in regard to the fan operation.

I have read the article by Mr. Crosby with considerable interest, as to me much of the subject matter as presented by Mr. Crosby is new. I was somewhat disappointed, however, to note the apparently small amount of attention that he paid to fans operating in the anthracite region, which, with few exceptions, require small driving power.

A survey of the fans in the anthracite region indicates that with few exceptions the fans are comparatively small. There are a few of 100 h.p., while the majority run below 50 h.p.

From the motor viewpoint of the article, as I have interpreted it, the application of variable speed motors as a fan drive is hardly the correct method of making use of the fan. Looking at it from the fan point of view, in the anthracite region, I believe that the prevailing opinion of mining men is that the fan should run at its constant maximum efficient peripheral speed, regardless of the quantity of air to be delivered, although there are quite a few cases where this is not always carried out, due, no doubt, to certain peculiar property conditions.

Mr. Crosby has said that the great majority of mine fan installations require an adjustable speed drive. To this I do not agree unless the arrangements do not permit of splitting the air, or the air required is exceptionally small compared to the ultimate fan capacity, in which case I believe a better plan is to use a smaller fan until such time as a larger fan might be required. In the last paragraph on page 1075 it is said that as the workings advance from day to day that the volume and pressure increases. This is not true. The volume decreases and the pressure increases, and if the fan is speeded up, to give more air, then pressure begins to increase at a great rate, with a considerable increase in power, and if that plan of operation is continued, then the limit of efficient operation is soon passed, the fan becomes inefficient, and the applied power is spent in overcoming practically resistance only, and very little is spent on the air, which is an uneconomical arrangement.

To produce a change in the air, by means of speed change appears to me to be rather bad practise, unless mining conditions prohibit any other method. It produces very poor fan economy, because the fan is not running at its most efficient peripheral speed. And on account of keeping so close to the air quantity, the gases may not be properly cleaned out, and it places the care of the fan in the hands of a person who may not, at all times, be under the direct control of the mine foreman.

On account of rapidly approaching the limit of efficient air volume, the fan becomes too small, or else the power apparatus is overloaded in overcoming the mine resistance. The correct way to vary the air quantity of a fan is by changing the air courses, or by splitting the current, thus giving an increased volume and a reduced water gage, and where this plan is carefully followed out, the fan runs at constant peripheral speed, and with slight variation in power. This also results in high fan economy as the applied power is spent more on the air than on the mine resistance, which is not the case in adjustable speed drives.

It is the displaced air that should be the measure of the power expended, and not the amount of resistance to be overcome. To illustrate this point: In a certain mine, the gangway was used as the intake, and the airway for the return. The water gage was two inches, the number of cubic feet was 98,000 and the fan was running at 50 rev. per min. It was necessary that the air be increased. To accomplish this the gangway and old airway were both made to serve as the intake, the headings being used for return. The result was that the fan delivered 178,000 cu. ft. of air, and the water gage dropped to 6/10 in., the fan speed remaining practically constant.

It is a fact that any normal size fan motor may be overloaded by reducing the resistance to a minimum, and working the fan on free air discharge. Conversely, the motor load decreases, when the fan displacement is the minimum, and the resistance is the maximum. Hence, between these limits the quantity of air delivered may be made anything, simply by varying the amount of resistance to be overcome, and as previously stated, this could be made by changing the airways themselves or by proper splitting.

From a consideration of these facts, it appears to me that constant speed motors are the proper style of drive to use, and should be used wherever possible. It is true that the ultimate variation in power on the motor may be large, but even between these extremes, the overall efficiency does not vary so greatly, as the fan efficiency under these conditions is quite high and constant over a wide range in air quantity, provided the fan is operated at its most economical peripheral speed.

Mr. Crosby has said that reliability is the first condition, and then comes economy. As far as reliability is concerned, it seems to me that the simplicity of the ordinary squirrel cage motor could be well capitalized in the matter of economy, when compared to the more complicated adjustable speed drive.

Wilfred Sykes: I am very much interested in Mr. Crosby's paper, and I think it is well that this subject of using three-phase commutator motors for regulating induction motors should be brought up before a meeting of this class. In a paper delivered before the Institute in New York by Dr. Meyer and myself, a great number of other schemes were mentioned that have been worked out, using commutator machines. There are

a great many combinations possible, and some of them perhaps simpler than that described by Mr. Crosby.

I notice in Fig. 7, showing a regulating set, that it really consists of three machines, and apparently the small machine on the right is an exciter.

Now, there is one point I want to bring out particularly, and that is the question of the amount of attention that you can give to a mine fan or to mining apparatus generally. The usual condition in a mine is that you start the machine working and you let it go and hope it will keep going, and until something connected with the machine breaks, nobody goes near it. In my mind it is questionable whether you can use a machine having the characteristics of the three-phase commutator motor under those conditions and get good results. These schemes have been mostly developed in Europe, and recently I saw a number of them operating and apparently working very well. I asked the operators a number of questions, the principal one of which was—"How much attention do you have to give to the machine?" And I got the same answer in all cases, that they had to look after these machines pretty well, give them more attention than they would to a straight induction motor. If that is the condition existing in Europe, where they have a very much better class of labor, looking after machinery around mines, where the attendants are much better educated, and have a much better knowledge of the characteristics of the machines, what is going to be the condition in this country? It seems to me we will have to make our machines here very much stronger in every way to meet operating conditions than do our European friends. I am convinced that for ordinary work you could not use the European induction motor and set it down under American conditions and get anything like the results achieved with the machines built in this country. Our operating conditions are different, and the machines have less skilled attention.

The question as to whether it is desirable to use any regulating arrangement at all, is open to quite a little discussion—I am referring now to fan motors. My impression is that in most mines possibly two speeds for the fan will meet all operating conditions, or will meet the conditions with very little sacrifice in economy, if you consider the yearly operating conditions. Now, you can get the two speeds either by a two-speed motor, or you can have some arrangement in which you have different pulley ratios. The mine fan has to be belted in nearly every case, because the fan speed is so low that the motor could not be direct-connected. In opening the mine you do not require so much air, but later, if you want to increase it, there is no hardship in changing the pulley ratio. A condition like that would not warrant the installation of an expensive regulating set. On the other hand, instead of the simple induction motor, you have, as shown in the sketch by Mr. Crosby, a three-machine regulating set, and I think when you come to consider, not only the first cost but the attention, and giving proper

consideration to the question of reliability, that there is quite some question as to whether you are justified in the majority of cases in using any scheme of this kind. I personally would very much like to see this thing worked out satisfactorily. On the other hand, I think we must go slowly in applying the European experience to American conditions. I know where it has been tried in a good many cases, and we have had disastrous results.

One of the schemes that was mentioned in the paper that we read in New York on this question involved only a single regulating machine, or, in case the voltage of the line was over 440, a single regulating machine and transformer. Such an arrangement seems to be a simplification of the one indicated by Mr. Crosby, but I think it will be a matter of some time before we can say that these equipments will be really satisfactory for American conditions. I think the experiment of trying out some of these things is one worth while, and such experiments may lead to developments which will greatly enhance the value of the induction motor and avoid the use of the direct-current variable speed motor around mines.

In all of our work in mining it is aimed to cut down the amount of direct-current machinery as much as possible, and try to use simple apparatus. Whether it is advisable to add on a regulating set, especially a machine like the three-phase commutator motor, which has limitations, is a question which can only be found out by experience.

One point arises, and that is the use of the three-phase commutator motor on 60 cycles. Most of our mines use alternating current for 60-cycle power, and that makes it a good deal harder to make a satisfactory commutator machine than if we were using 25-cycles. Of course, the commutator machine is in the rotor circuit of the induction motor, and consequently the frequency on it is variable, depending upon the speed drop required. With a scheme of this kind the condition is not quite so bad, when driving a fan, as it would be if you had a constant torque, because the current decreases as your frequency increases, and that facilitates commutation. I think the question, however, as to reliability of these regulating schemes, is one that has to be given a great deal of attention, and one that makes it desirable to go a little slow in installing apparatus of this kind.

George R. Wood: My impression is that this particular application is not intended as a panacea for all ills, and that it is not expected to use this in those cases where we have fully developed mines, with fans requiring practically constant speed. There are conditions, as we all know, where we have to open a mine with very little air required. In a short time it will require a large fan operating at increasing speed. Mr. Beers suggests putting in a small fan and operating it at suitable speed, and later changing the fan. This is a waste. If we can install a motor which will do everything from the start to the finish

of the operation, and get fair efficiency out of it, it would seem to me to be very desirable.

One of the greatest difficulties in the application of motors to mine fans is this requirement for variable speed, and engines, even though wasteful of power, are often installed as a matter of convenience. It is always desirable to have reserve speed and power in mine fan equipment, which ordinarily means inefficiency under normal conditions.

I believe the regulating system described by Mr. Crosby to be very desirable on fan motors of 300 h.p. and over, particularly for bituminous mines, with high and rapidly increasing water gage.

I am glad to note that a number of sets of this kind are being installed by the Pittsburgh Coal Co., both of the motor-generator style for large motors, and three-phase commutator type for small sizes. These will all use purchased power, and valuable data should soon be available.

H. C. Eddy: I ask Mr. Crosby as to the expense attached to the use of the installation—the cost of installation of such a device—as compared with the cost of the main motor, not necessarily in dollars and cents, but in percentages.

Graham Bright: I would like some practical mine ventilation man, to tell us why we cannot run a fan at a constant speed at all times, and throttle the outlet of the fan? They do this in hydraulic work, and why can it not be done in fan work? Let the fan run at the same speed all the time, and then apply some arrangement of putting a throttle at the inlet to the mine, so that as the mine develops we can open up a little more and allow more air to go through. There may be some objections to this scheme, and some of our practical ventilation men may tell us what they are. The efficiency may be somewhat lower than obtained by some of the variable speed methods but the simplicity is such that the continuity of service should be very high.

Mr. Crosby says that sometimes an ordinary wound-rotor motor is used and speed reduction obtained by cutting a resistance in the rotor circuit and that this scheme is objectionable on account of the speed changing with the load. As to a change in load, with a fixed speed, this cannot be, since with a fan running at practically constant speed, the load is constant, and you therefore will not get very much variation of speed with any resistance you put in the rotor circuit.

I would like to know if there is any difficulty in constructing a three-phase commutator motor for 60 cycles, as most of the mine circuits have 60 cycles instead of 25 cycles.

Mr. Crosby also remarks that changing pulleys is rather in the form of a makeshift. When we start a new mine, and the mine develops and requires more air, it is not a question of changing the pulley every day or two. The fan will probably run for six months or more, before it is necessary to change the pulley, and preparation can be made beforehand, so that the

change of the pulley will not be a hardship and can be accomplished with little or no delay in the mine operation.

H. Meyer-Delius: I think there would be no question at all that we would use a normal squirrel cage constant speed motor if the mine operators did not want to change the speed, as the first speaker, Mr. Beers, said. I am not at all familiar with these ventilators or fans, and I am told that it is a very difficult problem to deal with. I spoke to several mine operators in Europe, and they came to conclusions contrary to Mr. Beers,' but I do not know whether that is due to different conditions in European mines or to different opinions about the same conditions. The usual conditions in Europe are such that at first when the mine is small they do not need much air, and since they are using a fan and a motor equipment of the full capacity they have either to throttle the pipe or to reduce the speed, and I am told that reducing the speed is much more economical than to throttle the pipe. They mostly run at first at 30 per cent less speed than at the end, and that means a very big difference for the air volume, and apparently they have found out that even at this low speed the fan operates at pretty good efficiency.

I had the opportunity to visit practically all of the installations equipped with such regulating sets, which amount to about thirty or more, and I have some figures which remained in my mind, which may be of interest to you. There are some five or six 1200-h.p. motors, 5000 volts, 50 cycles, with 33 per cent speed reduction, and a maximum speed of about 300 rev. per min., and four plants, of about 900 h.p., with the same speed, and 30 to 25 per cent speed reduction, some of 600 h.p. with the same percentage of regulation, and some smaller ones, among them one of 200 h.p.

It was mentioned in this discussion that the average operator abroad is a much more trained and intelligent man than in America. I really do not know if that is actually true, because the men I have found watching these plants could not be called intelligent men, they mostly were old miners, they would turn the hand wheels according to their printed instructions and had no conception of what happened, but they were apparently able to operate these fans. I must mention that all of these fans were so installed that the operator had nothing else to do than to start a normal induction motor, and the switching over from the starting resistance to the regulating set, was done automatically, so that the man had really nothing else to do than throw in the main switch and cut out the resistances of the rotor, and I think for this work really there could be employed rather unintelligent people.

Moreover I saw some of these fans running entirely alone, the doors locked, and I think once a day a man came over to see if all was right; so I think in Europe, these equipments with regulating sets are apparently developed to such a state that they are very reliable machines, and I have never heard of any

complaint of their being unreliable. As far as I could see there, the commutation was perfectly correct, which is, of course, the main trouble with these commutator machines.

From some mine operators I got the figures that they had to pay about three-quarters of a cent per kw-hr. to the central station, from which they bought their power, and that in about one year, the additional investment for the regulating sets was paid by the saving of current, and since the speed of these fans has to be reduced, three, four, or five years, they believed that that equipment was a very good investment.

Mr. Sykes mentioned another scheme, using a frequency changer, a single auxiliary machine. With the frequency changer there were also tests made in Europe, and as far as I know two of them were installed; one was a 600-h.p. fan motor, with 33 per cent regulation, and as far as I am informed this scheme was abandoned because they could not get the frequency changer to commutate at the lower speeds and that is my experience also, that is, that these frequency changers have entirely different commutation conditions from normal commutator machines, and it seems to me so far very difficult to get satisfactory commutation at least, at larger outputs.

W. O. Oschmann: The statement has been made here that mine fans are usually put in operation and then not looked after at all, until something happens. I would not like that statement to be published in the PROCEEDINGS or go into the TRANSACTIONS, without making a defense, for the miners of Pennsylvania in particular. I have here a little book containing the Bituminous Mine Law of the State of Pennsylvania. It plainly states that each fan ventilating a mine must be provided with a recording gage that records the revolutions of the fan, or the pressure entering into the mine at all times, also that the fan must be inspected periodically. The provision is also made that in case anything goes wrong with this fan it must not be stopped, even for repairs, until the mine foreman has been notified, who, when he considers it safe, will allow them to stop that fan in order to repair it. In case the fan does stop, due to accident or otherwise, they are compelled to withdraw the miners from the mine until the fan has been made safe. For that reason, a great many companies have two fans, one in operation and one in reserve, so in case anything goes wrong with either fan they can immediately put another fan into operation, and there is quite a stiff penalty attached to any violation of this law.

B. M. Fast: In the territory I cover I find that the fan requirements vary from 25 to 50 h.p., and in no case have I found them larger. Up to the present time, most mines are operated single shift, but since they have been buying power the question has arisen of operating double shifts, and thereby saving in cost of operation. That time is coming, and even now the operators are talking of developing the mines and running

double shift. During the night shift only 25 or less percentage of the men are underground, as in comparison with the day shift, and therefore it is not necessary to have as much air during the night shift. The question arises: can we not save the operator a certain amount of power cost by a change of speed of the fan? If it can be done, the central station man should have the credit of doing it, if it is possible, because the operator is only too glad to save in his cost.

In matters of this kind it seems to me there is only one of two things to do. First, as to the question of buying power for a new mine, I simply change the pulley speeds and it solves the problem, but for a mine that has been developed and wants to run cutters or pump-men under ground at night, I would rather have a split ring motor, with external resistance, or a two-speed motor, doubling the number of poles for the lower speed.

The next question the operator asks is, which of these it is more advisable to install and operate. If the two-speed motor is simpler and has fewer parts to get out of order, and these fans will run without attention, they naturally prefer that motor. The two-speed motor may be less complicated, and there may be a saving in power, as compared with the variable speed motor, yet the cost is very much higher.

The next question I submitted to manufacturers was with reference to variation in speed between full speed and half speed. The result I found was that there was not 5 per cent difference in half speed operation on the two-speed and variable speed fan motors. Whether or not the data submitted to me by these companies is reliable, I am not in position to say, but it showed less than 5 per cent difference in the amount of power used. So that from my experience the two-speed fan motor is preferable, rather than the variable speed, due to the fact that the simpler construction requires less attention. In this particular case it was a 40-h.p. motor, variable speed, requiring on half speed of the fan something like 15 h.p. The data on the two-speed fan showed that it required 15 h.p. on half speed. It is simply a question of which motor you want to buy in that case. It seems to me that will apply to the territory I covered.

H. L. Beach: I had occasion some four or five years ago to purchase a fan and motors for a mine where we were doing developing work to a considerable extent. The exact figures of the amount of air required have slipped my mind now, but I know that we needed a total of 200 h.p. to operate the fan at full capacity. At the time the fan was to be installed they needed possibly only one-third of that. My purchase consisted of two squirrel cage motors, manufactured at the same time, so as to get the characteristics identical, tested and guaranteed to divide the load equally at the same speed. When tested the motors were fastened together with a flange coupling, and the load driven by a belt using the coupling as a pulley, the load dividing within a per cent or so between the two motors. I then set one motor

on some temporary work we had, and put the other motor on the one fan. That motor has been running something like three years, and they have not had occasion yet to change the pulley. The arrangement was that we would make a high pulley ratio to start with, and as the requirements for air increased they would decrease the pulley ratio and speed up the fan. The arrangement has been absolutely satisfactory, and has not given a moment's trouble or delay in any way, and so far they have all the air they want with one motor and the original pulley layout. It is ready at any time to put another pulley on. They can make one increase in speed with the present motor, and then by releasing the other motor they can increase the speed until the full capacity is obtained. I can, for my part, see no reason for the large expense and complication of variable speed outfits. The change in pulley is not a proposition which comes up every day, but a proposition which may come up only once in two or three years. Two or three fans are usually required for a large mine anyway and it is a simple proposition to shut down one or more at night and run all during the day.

F. B. Crosby: The discussion aroused by this paper would appear to be ample justification for its presentation. The particular point about which the discussion has chiefly centered, namely, the desirability of adjustable speed drives for mine fans, was taken for granted by the writer. As stated in the paper there is a somewhat limited field in which constant speed drives are satisfactory, but the very great percentage of requests for adjustable speed fan drives as compared with constant speed applications which have to come to the writer in his professional capacity, as well as the ready defence of the adjustable speed drive by many experienced mine operators and engineers this afternoon, can leave no doubt as to its desirability.

The method of obtaining speed control by dynamic regulation as described has been developed to meet an existing need. These speed regulating sets and brush shifting motors are the result, and not the cause, of the demand for adjustable speed drives. The entire range of horse power capacities and speeds ordinarily required can be simply and more efficiently met by one or the other of these two equipments than by any other commercially practicable drive yet devised.

For small drives, 100 h.p. or less, the extreme simplicity of the brush-shifting motor and control is especially desirable since the single motor involved is started, stopped, reversed and the speed controlled by merely shifting the brushes.

It has been suggested that the regulating set introduces a complexity of control equipment prohibitive in the hands of the average fan attendent. This feature has, I believe, been unduly emphasized.

Considering the results obtained nothing can be simpler than the operation of the set. The main motor is started in the usual manner by simply closing the primary oil switch and throwing

the controller to the full-on position. The motor generator is started by means of a standard induction motor compensator. Electrical equilibrium between the main motor and motor generator is absolutely automatic. Any desired speed of the main motor within limits of design is obtained simply by adjusting the exciter field rheostat.

Referring to Mr. Eddy's request for information regarding costs, it is difficult to answer such a question, except in general terms, owing to the many variable factors involved. The cost is obviously more than for a single-speed motor and depends upon the frequency and range of speed required. For 25-cycle equipment designed to give 20 per cent speed regulation on the main motor, the complete equipment including main motor and control may cost from 15 per cent to 20 per cent more than a two-speed motor designed for the upper and lower speeds.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

CENTRAL STATION POWER FOR MINES

BY J. S. JENKS

The subject of this meeting covers such a broad field that it would be folly to undertake to cover more than a limited portion of any particular branch; hence I will deal only with the historical side of the question as it has to do with the development of central station service in connection with coal mining on the West Penn system.

Central station power for mine service has been greatly handicapped by the prejudice of some mining engineers and mine inspectors who have actually fought the installation of central station power, stating that central station service was not as reliable as an isolated plant, was more dangerous on account of the high voltage and more costly. They often eliminated all cost of plant labor and fuel when making comparisons between central station service and isolated plants, arguing that the plant labor would have to be around the mine at any rate, and that the cost of fuel was so small to the mining company that it should not be considered.

In order to overcome these objections it was necessary to prove the reliability of central station service and its advantages. The objection of the mine inspectors was the hardest to overcome, even after the mine operators were convinced that central station service was more economical and were in favor of installing it the mine inspectors frequently prohibited central station service for some uses in and about the mines, particularly for fan service.

They argued that transmission and distributing lines, of necessity, made central station service more liable to accidents and acts of God beyond the control of man, contending that mine ventilation was of such importance that no mining company

should be dependent on another corporation for its power for fan operation. It was only after years of successful operation of all other classes of mine service that we were able to overcome this prejudice and succeed in getting the mine inspectors to approve central station service for fans, much less recommend it.

The mining engineer, and the electrical employees, opposed central station service for obvious reasons, one of which, frequently frankly admitted, was, that with central station service they would have no job. The truth of the matter has been that central station service has actually enlarged their field of labor, as more mines are being electrified every day on account of the many advantages of central station service, thus requiring the services of an engineer and electricians to most efficiently install and operate central station power. High grade engineering and labor pays such great returns on the investment that the demand for first class men is continually increasing. While on the other hand it is an admitted fact that almost any mine foreman or master mechanic could install and operate a steam drive or a d-c. isolated plant, this very frequently was a most uneconomical operation, often actually costing many times what it was supposed to. The lack of electrical engineering in the early days of central station service was a large factor in retarding its growth as will be shown by the initial installation in this territory.

This first installation of central station service in a mine on the West Penn system was made at the Larimer mine of the Westmoreland Coal Company in 1896. It consisted of a 120-h.p., 4,000-volt, single-phase, 133-cycle, induction type synchronous motor, belted to 100-kw., 500-volt, direct-current, multipolar generator. The motor was excited by a belt-driven exciter and started by a single-phase, 100-volt motor which actuated through shifting belts. The switchboard consisted of standard d-c. marble panel with ammeter, voltmeter, circuit breaker and switches. The a-c. board consisted of a wooden panel having mounted on it a small two-pole oil switch for controlling the large motor, a two-pole knife switch for the starting motor, pilot and synchronizing lamps. This apparatus was located in an underground substation as it was feared it might be damaged by employees during strike periods if it were above ground.

In order to supply this service there was installed at the power house of the Irwin Electric Light & Power Company at Manor, one 150-kw., single-phase, 2000-volt, 133-cycle alternator and 125-kw., 2200 to 4400-volt, 60-cycle transformer for raising the generator voltage to the transmission and motor voltage.

The line consisted of two No. 4 insulated wires carried by glass insulators on a two-pin crossarm over private right-of-way from Manor to the sub-station located near Circleville, except through the town of Irwin where it was on the street. The length of this line was about 5 miles (8 km.) A telephone line consisting of duplex insulated wire was strung on a ridge pin on the top of the pole. The wire entrance to the underground substation was made by sinking a bore hole through which lead cables were carried to an underground tunnel which led to the machine room. In order to protect the lead cable where it entered the ground, a high circular stone wall was built around the bore hole.

The apparatus supplied from this substation consisted of six mining machines, a 10 h.p. pump and a 60-h.p. haulage, but no fan service was supplied for reasons already explained.

The first trouble that developed was the falling in of the roof of the substation, which not only damaged the apparatus, but put the mine out of service for some time until the debris could be removed and a brick lining put in to prevent a recurrence of similar trouble. This brick lining sweated so that it made all the apparatus wet, which resulted in frequent burn-outs of the starting motor, which stood idle for long periods. In order to insure starting, duplicate starting motors were provided and at times it was a problem to keep one in condition for service. The difficulty of sweating was partially overcome by putting a wooden lining inside the brickwork.

The next difficulty arose from a breakdown in the lead cable caused by lightning. This had the effect of charging everything in the substation. It was overcome by removing the lead from the cable and supporting it on glass insulators, except where it passed through the bore hole.

The next weakness developed in the oil switch which consisted of eight ½ in. (1.27 cm.) brass rods working through small brass bushings, mounted on a wooden board submerged in oil. This two-pole switch had eight breaks of about ¾ in. (1.9 cm.) each and was contained in a tank 8 by 10 by 9 in. (20.3 by 25.4 by 22.8 cm.) and operated by hand-wheel and pinion, which worked on a rack pulling the rods out of the bushings. This made a very slow operating switch with which it was very difficult to synchronize. After numerous interruptions caused by failures of this switch a make-shift switch consisting of an ordinary two-pole, two-break, knife switch on a marble base was mounted on insulators in the bottom of a half barrel. The switch handle was

removed and a broomstick tied to the cross-bar with a belt lace. Leads were brought over the edge of the barrel and connected to the switch. The barrel was filled with oil. The switch was operated by pulling or pushing on the broomstick. This switch was so much more easily operated and such improvement was made in the time of synchronizing that the consumer would not have it changed and it remained in service until the substation was finally abandoned on account of the mine being worked out.

The Irwin Electric Light & Power Company was acquired by the West Penn interests and in 1905 the 133-cycle power house at Manor was discontinued and service established from a 60-cycle turbine station at Connellsville through 28.52 miles (45.5 km.) of 22,000-volt transmission lines and a substation at Manor. This necessitated the reconstruction of the motors from 133 to 60 cycles. The work on the large motor was done in the field and the starting motors were sent to the factory one at a time. This reconstruction had the effect of reducing the capacity of the motors and resulted disastrously in the case of the starting motors, making it necessary to provide larger motors.

The next trouble to develop, was rather peculiar in that the large motor started to drop out of step without any apparent cause and would drop out when hauling practically no load. This was a very puzzling circumstance and no amount of adjusting by attendant seemed to remedy the trouble. It was found, however, when the supply from Connellsville was generated by a single unit that this trouble was most pronounced and later discovered that there was a splice in the belt between the motor and generator that caused little jerks which would get in step with the governor mechanism on the turbine, causing the turbine to hunt. This hunting was exaggerated in the motor, making it drop out of step. The remedy for this trouble consisted in direct-connecting the motor and generator, which happened to be the same speed. On account of the high voltage of the motor it was necessary to have the motor frame insulated and a satisfactory insulating coupling became the question. This was solved by turning the shafts end to end, setting the pulleys about six inches apart, drilling and tapering the rim of the pulleys for cap screws and laying a piece of belt around inside of both pulley rims and securing it in place with cap screws. This proved a very satisfactory flexible insulating coupling, which gave no trouble and operated for a number of years until the mine was worked out.

Notwithstanding these difficulties enumerated, this installation

proved a very satisfactory one to the mining company, saving them a considerable amount of money, even though the rate charged was several times greater than that charged for similar service to-day, and it led to many other large installations.

The first mine where West Penn service was used for fan operation was at the Penn Gas Coal Company's mine near Penn Station, and consisted of a 100-h.p., 500-volt d-c. motor, belted to the fan. This was installed about 1901 when the mine was completely electrified with direct current. The installation consisted of numerous pumps, mine machinery and a large haulage. The fan operated until 1907 when this motor was replaced by a 200-h.p. a-c. two-phase, 60-cycle motor. This installation, which originally consisted of about 500 h.p., has been increased from time to time until it now has about 1250 h. p. in electric motors.

In 1907 our first high-tension installation was made at a coal mine. This was made at the Noami Mine of the United Coal Company near Fayette City. In this case the Coal Company built its own substation and bought current at 22,000 volts installing three 200-kw. 22,000 to 440-volt transformers, one 300- and one 150-kw. synchronous motor-generator sets, one 150-h.p. a-c. haulage, 100-h.p. chain lift, two 75-h.p. fan motors, a-c. pumps and numerous haulage locomotives and mining machines. This installation was of particular interest as it was the first one where engineering had very careful consideration and was our first a-c. haulage.

Another very prominent example of a coal mine installation where the most minute detail was worked out by the engineers in charge with the idea of producing the most efficient results is illustrated by the Keystone Coal Company's installation at its Crows Nest substation. Here 1500 h.p. is delivered at 2300 volts from 22,000-volt transformers installed in the substation, together with the necessary switches and lightning protection. This installation consists of 750 h.p., a-c. haulage, two 300-kw. synchronous motor-generator sets, two 150-h.p., a-c. pumps and innumerable locomotives, mining machines and small motors.

While the growth of central station service was very slow at first, it is now growing very fast, and from the original installation in 1896 of 120 h.p. we have steadily added all kinds of mine installations until at the present time we have in operation 76 coal mines consisting of 14,831 h.p. and have contracts with 10 companies which aggregate 5,701 h.p which is being installed as rapidly as possible. This will make a

total of 20,532 h.p. In addition to this we are at the present time figuring with a number of coal companies and have every reason to believe that in a short time we will have under contract more than 10,000 h.p. additional, which will increase our total to over 30,000 h.p. in coal mine service only.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 18, 1913.

Copyright 1913. By A.I.E.E.

CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE LACKAWANNA R.R. CO.

BY H. M. WARREN AND A. S. BIESECKER

In view of the fact that practically no data of this nature are available and as the Lackawanna Railroad Company has a large number of substations to which the rated connected loads widely differ, the writers were led to conduct a series of tests, the result of which form the basis of this paper.

Tests were made on 15 substations ranging in size from 150 to 700 kw. The apparatus in these stations consists of 60-cycle, six-phase diametrically connected synchronous converters delivering direct current at 275 volts, step-down transformers of either the single or three phase type, and the necessary a-c. and d-c. switching apparatus. These substations are usually located on the surface at the colliery, and the three-phase high-tension power is furnished from central stations.

The power apparatus driven from the substations consists of locomotives, hoists, pumps, and under-cutting machines. The locomotives vary in size from 7 to 13 tons and are usually geared to operate at a speed of from six to eight miles (9.6 to 12.8 km.) per hour at full load. Although the locomotive weights vary, about 80 per cent of the total number weigh seven tons or less. All of the locomotives have double motor equipments with series-parallel controllers. The motor equipments average about 10 h.p. (railway rating) per ton of locomotive weight. The d-c. hoists operate on either slopes or planes and vary in size from 20 to 160 h.p. As most of the large pumps are driven by a-c. motors, the d-c. pumping sets are usually small in size and operate intermittently. The power required for undercutting machines

is at present comparatively small. It is, therefore, important to note that about 75 per cent of all d-c. power supplied from these substations is used by locomotives and that 80 per cent of all locomotives are rated at 70 h.p. or less.

The tests on these substations were conducted as follows:

In order to obtain accurate readings, an a-c. single-phase watt-hour meter with high geared dials was obtained. This was connected in one phase of the a-c. end of the synchronous converter and readings taken every half hour. A record of the peaks was obtained by connecting a graphic ammeter which was geared to give a paper speed of 7½ in. (18.8 cm.) per minute in the d-c side of the converter. A note was also made of the machines operating in the mine at the time of the tests.

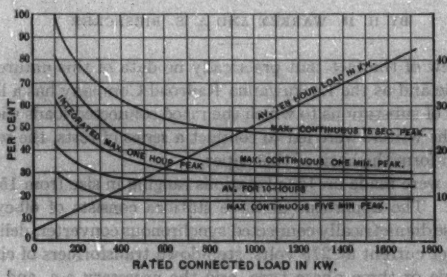


FIG. 1—SUBSTATION LOAD AND PEAKS BASED ON SYNCHRONOUS CONVERTER OUTPUT

The rated connected loads were based on the following motor ratings:

Electric locomotive—10 h.p. per ton.
Hoist motors (railway type) —one hour rating.
Pumps—Name plate—continuous rating.
Undercutting machines—one hour rating.

The total of these horse-power ratings was reduced to kilowatts in determining the kilowatts rating of the total connected load.

After the above test data were obtained, a tabulation was made showing the maximum peaks for 15 seconds, one minute, five minutes, and one hour; the average load for a ten-hour day; the kilowatt-hours per month, and the rated connected kilowatt load for each substation. In working up these data, the 15-second, and also the one-and five-minute peaks were measured

on the graphic ammeter paper as block peaks, while the one hour peaks were taken from the watt-hour meter readings and are, therefore, the integrated peaks. However, after determining the d-c. peaks, an amount equivalent to the synchronous converter losses was added, so that all tabulations were made on the converter input basis.

From the tabulations, a set of curves was then plotted as shown in Fig. 2. On this chart the abscissa represents the rated connected load in kilowatts. The lower curve representing the kilowatt-hour per month is read on the right hand margin, while other curves are read in kilowatt on the left hand margin. From this chart other curves and factors were derived which will be discussed later.

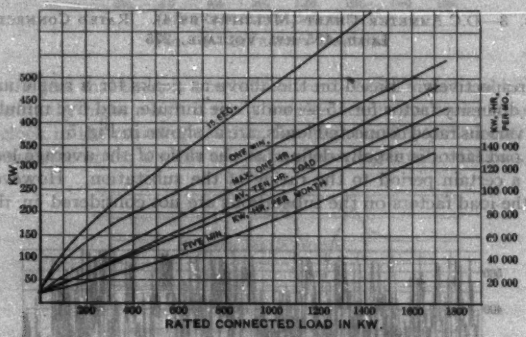


FIG. 2—SUBSTATION LOADS AND PEAKS

From the above, we have been able to make some interesting deductions regarding diversity factors and load factors. Diversity factor has been defined as the ratio of the sum of the maxima of the subdivisions of any part of the system to the coincident maximum demand observed at the point of supply. For the present we will, therefore, consider the subdivisions as loads taken by the individual locomotive, hoist, etc., and the point of supply as the a-c. side of the converters. In order to illustrate how the diversity factor increases from unity to higher values as the number of units and consequently the rated connected load is increased, we have shown in Figs. 3 and 4, sections of graphic ammeter charts taken at different substations. Fig. 3 shows the

load on a small substation to which the rated connected load was only 465 kw., while Fig. 4 shows a similar curve for a substation to which the rated connected load was 1720 kw. From tests made on a seven-ton locomotive, rated at 70 h.p. or 52.5 kw., we find that the maximum continuous peaks in per cent of its rating for 15 seconds, one minute and five minutes, are 180, 100, and

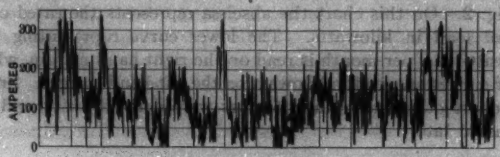


FIG. 3—D.C. AMMETER CHART (MULTIPLY BY 4). RATED CONNECTED LOAD, 465 KW. VOLTAGE, 275

60 respectively. Based on the above as peaks for a single unit the diversity factor for 15 seconds, one minute, and five minutes for various rated connected loads, are as shown in Fig. 5.

Load factor is usually defined as the ratio of the average load for a certain period to the rating of the substation. However, as the load factors on the substations are not considered in this

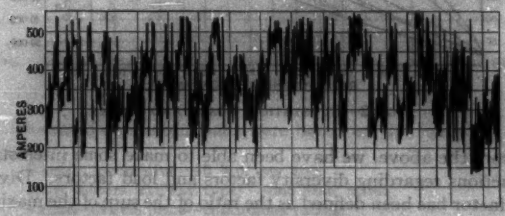


FIG. 4—D.C. AMMETER CHART (MULTIPLY BY 4). RATED CONNECTED LOAD, 1720 KW. VOLTAGE, 275

paper, we have expressed all load factors as the ratio of the average loads on the substations to the rated connected loads. By so doing, any data contained in the paper become applicable to other similar installations.

Fig. 6 shows a 10-hour load curve taken on one of the largest substations. This curve was plotted from watt-hour meter read-

ings taken every half hour. It will be noted that it has about the same characteristics as are generally found in shops or factories where the consumption of power depends on the activity of the employees operating the machines. However, there is a low point in this curve which occurs about nine o'clock. This is due

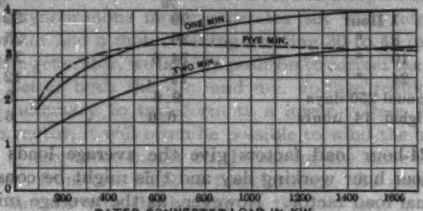


FIG. 5—DIVERSITY FACTORS

to the fact that there is a certain amount of coal mined and loaded during the night which is ready for the locomotive crews at seven o'clock in the morning. After this night coal is pulled out, the crews ease up for a while and take a morning lunch. During this

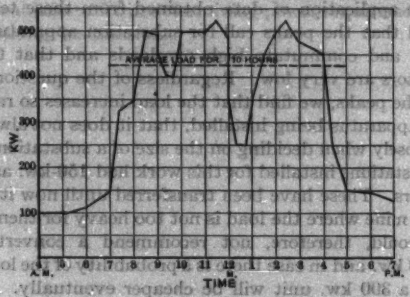


FIG. 6—A TYPICAL SUBSTATION LOAD

time, the day miners have been loading coal which keeps the locomotives busy until about 11:30 when the load begins to drop again. The substation on which the above curve was taken had a rated connected load of 1720 kw. which consisted of eight 10-ton, and 20 7-ton locomotives, and a small hoist. The average

ten hour load factor was 24.6 per cent whereas the average for all substations was 24 per cent. The following tabulations give the load factors for various lengths of time for this largest station and the average of fifteen stations tested:

Station	Largest %	Average %
1 Hour	29	32
8 "	26	25.5
10 "	24.6	24
24 "	14	12.5
Annual 250 days	9.6	8.6
(Night) 14 hours	6.6	6.2

The 24-hour load factors give the average loads during a twenty-four hour working day and this might be considered as the annual load factor. However, as the average mine is not operated over 250 days during the year, the load factor on this basis for all stations tested is 8.6 per cent. It is interesting to note that the ratio of the power used during the ten hour working day to the total used during the 24 hours was 73 per cent on the largest station and 79 per cent was the average for all stations. The average 14-hour night load is, therefore, 6.2 per cent of the rated connected load.

In the application of data obtained from these tests, it will be noted that the peaks call for substation apparatus designed to carry and commutate high overloads and that the annual load factors are very low. Regardless of the question of taking care of the peaks, we find that the load increases so rapidly, due to new apparatus being installed, that it does not always pay to figure closely when deciding on the size of a substation. Some of the first stations installed for this work had 150-kw. and 200-kw. converters. These have been transferred until now it is difficult to find a mine where the load is not too heavy for them.

We would, therefore, not recommend a converter smaller than 200 kw. and in case there is a probability of the load growing rapidly, a 300 kw. unit will be cheaper eventually. There are certain conditions where motor-generator sets work out more advantageously even though the initial cost may be much higher. Let us assume a condition where the substation is to be located near an a-c. motor-driven coal breaker, both of which are to be fed from a central station over a transmission line. The breaker motors will pull a load on which the power factor will be poor and this load together with the hoisting and pumping load will be so

large in comparison to the substation load that the small amount of leading current obtainable from a converter, will not compensate for the lagging current taken by the induction motors. The above will result in poor voltage regulation on transformers and transmission line, and the attending bad effects due to poor power factors on a central station. If instead of using a converter we install a synchronous motor-generator set with interpoles on the generator and a motor having a rating 30 to 40 per cent in excess of the generator, we are in a position to correct the power factor, and better both the d-c. and a-c. voltage regulation. Where it is necessary to transform to a lower voltage for the synchronous motor, it will often be possible to wind the breaker motors and synchronous motor on the set for the same voltage and feed them from one bank of transformers. By combining the leading current with the lagging on the low-tension side of one bank, the kilowatt-ampere rating is very much reduced from that required for separate transformers. There is also a decrease in the cost per kilowatt-ampere due to the units being larger.

While the data obtained from this investigation will probably not be of any particular value except for use in connection with electrical installations in anthracite mines, it is believed that on account of the number of stations tested that the data will, at least, be of great assistance in determining power requirements for anthracite mining installations.

DISCUSSION ON "CENTRAL STATION POWER FOR MINES" (JENKS) AND "CHARACTERISTICS OF SUBSTATION LOADS AT THE ANTHRACITE COLLIERIES OF THE D.L. & W.RY. CO." (WARREN AND BIESECKER), PITTSBURGH, PA., APRIL 18, 1913.

Graham Bright: Mr. Jenks has given us some very interesting historical matter. In the first part of his paper he mentions the early prejudice of the operators in regard to the purchase of central station power. I think this early prejudice was justifiable, when we consider that central stations had not made any records for themselves, and the operator had no way of telling what the continuity of service was going to be. As we know, in any new industry the pioneer usually stands the cost of development while those who follow reap the benefits, and you can hardly blame those early operators for having a prejudice against the use of central station power.

I think a great deal of credit is due to the operating forces of the central stations in bringing the continuity of service to such a high degree of efficiency. We have records of long periods of operation with little or no delays, and records made by such companies as the West Penn Railways Co. have given to operators confidence in central station power, and have made the sale of such power a much easier matter than formerly.

There is one point I would like to bring out in connection with the paper by Messrs. Warren and Biesecker which has given us a great deal of valuable information on actual mine conditions, and that is, referring to Figs. 1 and 2, you will notice that the five-minute peak is considerably smaller than the integrated average for 10 hours. That brings up the point of just what kind of a peak to use on which to determine the fixed charge. This illustrates the fact that the block peak is not the proper one on which to base the fixed charge, because here is a case in which the block peak is considerably less than the average for 10 hours. You can see it is not a square deal to the central station to use a peak load which is less than the average 10-hour load as a basis for the fixed charge. It should be the integrated peak rather than block peak, and these two curves illustrate that particular point very strongly. In fact a power circuit can be so manipulated that there will be little or no block peaks at all.

W. A. Thomas: Various statements of load factor, and particularly those brought out in the paper by Messrs. Warren and Biesecker, show the necessity of coming to a common basis in determining the expression of load factor. This is perfectly correct as explained by Mr. Warren, but unless you give a good deal of thought in transposing from one statement to another, we are led to confusion. In this case we have not only the load factor stated in terms of the average demand to the connected load, but we have the connected load rated on both constant and intermittent basis, and while, as I said before, it is perfectly legitimate and correct, we ought, in using it, to get to a common basis

of understanding. Of course, one statement of load factor is the ratio of the average consumption to the capacity of the substation. Another one is that which Mr. Bright touched on, the ratio of the average load to a given peak, five minutes integrated peak, or 15 minutes integrated peak. The point I wish to lay particular stress upon is the desirability of coming to a common basis for determining load factor and reducing the amount of labor necessary to transpose from one to another. I do not mean this as a criticism of the paper in any way. I consider that the data which is submitted in this paper is a most valuable contribution to the art, and one which will be of extreme value in this very active campaign on the part of the operators of central power stations in the coal mining regions.

J. Paul Clayton: The characteristics of coal mine loads as shown by this paper are extremely low annual load factors. The annual load factor controls almost directly the cost of producing power in any plant, such as the installation under discussion, and further to illustrate this point I have recomputed the cost presented in Mr. Beers' paper presented this morning, on the basis of lower annual load factors as they actually occur in these mines. In Mr. Beers' paper of this morning, the total cost of producing power in a station of 1000-kw. capacity, operating at 50 per cent load factor, was given as $35,000 on an annual output of 4,380,000 kw-hr. or a total cost of eight mills per kw-hr. Reducing this cost to the basis of a 20 per cent. annual load factor, which is rather high for mines with which I am familiar in Illinois, we have a total cost of $31,200 (about the only difference in the cost being the item of coal) and the total cost works out at 1.8 cents per kw-hr. Reducing this load factor further to 15 per cent, the cost of operation is reduced from $35,000 at 50 per cent load factor to $30,630, at 15 per cent load factor, or a total cost per kw-hr. of 2.4 cents.

In the operation of such a station for Illinois mine conditions, serving only one mine, on one shift per day operation, 200 days per year, you could not secure an annual load factor of 20 per cent. The load factor as I am using it, is the actual energy consumption in a year divided by the energy consumption which would have taken place had the actual 15-minute annual maximum demand basis been carried on throughout the year. This analysis shows that the probable cost of energy for the installation of the plant cited, when used under the conditions obtaining in the paper or under conditions obtaining in the bituminous mines of Illinois, would be in excess of two cents per kw-hr. instead of 8 mills per kw-hr. It would be perfectly possible to make power in that same station for about 6 mills per kw-hr. if you could obtain a 100 per cent load factor, but I believe the publication of such costs without adequate explanation of the effect of load factor on them gives a wrong impression as to the cost of producing power under the conditions obtaining in the vast majority of all coal mines.

George R. Wood: I think it important that we come to a better understanding of what we mean by the term load factor. In the course of this meeting we have had three or four varieties of this factor, based on connected load, station capacity, instantaneous, one minute and 15 minute integrated peak, etc. In other words, every central station figures customers' load factor as the ratio of average load to maximum demand, as defined by contract. It seems to me probable that an integrated peak over some such period as five, ten or fifteen minutes will ultimately become standard for determining maximum demand, but in the meantime a definition should accompany reference to "load factor."

H. M. Warren: If the gentleman who just spoke, contemplates using the figures I quote, as a basis of the kw-hr. cost, he should bear in mind that the information in the paper refers only to the direct current used in the mines in question, and that the large amount of alternating current power used, has not been considered. The load factor of our central station is 65 per cent, and is figured on the average yearly load in kilowatts compared to the rating of the station.

George H. Morse: It would be interesting to know how the gentlemen who made the calculations on their load factors proceeded in making these calculations. I think there are various ways in which individuals would proceed, and if Mr. Clayton would care to state how he made his calculations, I think we would be much interested in hearing from him.

J. Paul Clayton: As to the basis of the costs of power, I took the cost as given on page 1038 of Mr. Beers' paper and assumed that, for practical purposes, the fixed charges remained exactly as given, and I think that is approximately true and that the item of coal, easily the largest single item, varied with the load factor. If we reduce the load factor from 50 per cent to 25 per cent, the coal consumption will be something more than half the coal consumption at the high load factor, as it does not fall off in proportion because the efficiency of boilers and turbines would be less.

In computing the cost given in my previous discussion I assumed that the coal consumption at 20 per cent load factor was half that at 50 per cent load factor and in obtaining the load factor at 15 per cent I have assumed that the coal consumed at the 20 per cent load factor was reduced by 15 per cent, and that the other items in the operating cost would be approximately the same.

C. W. PenDell: The item of load factor, as the Chair has said, is one that we should have a definite idea upon. It is something that should be settled and defined, and not a thing that one engineer should have a rule for talking on, in one line, and another engineer have another rule for talking on, in another line. If I design a plant to operate a mine and put in 1000 kw., and another man puts in 500 kw., that should not affect the load factor. The

consumption of the two plants will be the same. The load factor on the 1,000-kw. plant would be one-half what the load factor would be on the 500-kw. plant, if you base your load factor upon the size of the plant. Load factor is something definite, not something ethereal. It is the relation between the average load 24 hours a day and the maximum demand. You may take the maximum demand for five minutes, or you may take it for an hour, according to the way your contract reads. Whether you take a five-minute peak or a 30-minute peak, will probably make about 15 per cent difference in your load factor; that is, a load factor of 40 per cent on a 30-minute basis would be equivalent to 0.85 times 40 per cent on a five-minute basis. Load factor on a five-minute basis will be lower than on the 30-minute basis, because the maximum for 30 minutes will not be as high as the maximum for five minutes. Many base load factor on the operating time for the mine. According to the central station idea, and I am a central station man, the load factor should go over the whole 24-hour period. The reason for that is; supposing we have a plant which has 100 h.p. maximum demand, the average running load is 50 h.p. and the running time is 10 hours per day. If you base the load factor upon the hours during which the plant is running, you get a 50 per cent load factor. If the plant runs 20 hours per day, with an average load of 50 h.p., and you base your load factor upon the running hours, you still have a 50 per cent load factor. Under this method you have nothing on which to base a comparison of one plant as against another; so that in the central station field we have adopted the general ruling that load factor is the ratio of the kw-hr. consumption divided by the total number of hours in the period under consideration, and that result divided by the maximum demand as determined by the contract. To base the load factor upon the size of the installation is, according to my idea, erroneous. I may come along and install a plant with a 1000-h.p. unit—I do not know the business perhaps—I put 1000 h.p. in the plant to be safe; another man comes along who knows the industry, and puts in a 500-h.p. plant—why should the load factor of that plant, which is a concrete item, be dependent upon whether I know that line of industry, or whether I do not know it? Load factor is something which we can see if we stop to consider the curve. You have a certain curve running along with certain peaks in it; there is your load factor. It is the relation of the average line across the chart to the high point that constitutes the peak.

Graham Bright: I ask Mr. PenDell whether he has reference to the integrated peak or the block peak.

C. W. PenDell: The integrated peak is the only proper peak. Some contracts on railway lines, where the load fluctuates seriously, are based upon the highest instantaneous demand. It all depends upon the capacity of the station furnishing the load and the class of business you are serving.

I was talking with Mr. Jenks a few minutes ago relative to

mine hoists. He showed us a picture of a 750-h.p. haulage system. In Illinois we have mine hoisting outfits from 400 h.p. to 1800 h.p. We have not felt that we could take these hoists directly onto our lines, and have asked the customers to interpose flywheel motor-generator sets between the hoists and our lines. Now, with the flywheel motor-generator set we would integrate our peak. If we felt, perhaps, that we could stand the load directly on the line, we might give these parties contracts stipulating that the peak should be the highest swing of the needle on the chart. The integrated peak has been adopted in probably 90 per cent of all maximum demand contracts for central station companies. There are four common durations of peak, 5 minutes, 15 minutes, 30 minutes and one hour. Five-minute peaks have been adopted through the central states for coal mines and large stone quarries. Fifteen-minute peaks have been adopted by some companies for that class of business. General power is now being taken on over a great part of the country on 30-minute peaks. Railway contracts, large interurban systems, are going on commonly with 60-minute peaks. In addition to having the single 5-minute, 15-minute, 30-minute or 60-minute peaks, contracts are made wherein the maximum is based upon three 5-minute, 15-minute, 30-minute or 60-minute periods, no two of which periods shall be taken on the same day. That will, of course, give a lower maximum demand than a single peak.

George R. Wood: Perhaps we have no right to be surprised when the coal operator doubts our figures showing what he will get under these various rate schemes, and I cannot much blame the operators for refusing to buy power except at so many cents per ton of coal produced, and, indeed, power has been contracted for on that basis.

P. M. Lincoln: Reference has been made to 5-minute, 15-minute, 30-minute and 60-minute peaks. On the lines of the Niagara, Lockport and Ontario Power Company, which distributes power from Niagara Falls through Central New York, they have adopted the one-minute peak. I am inclined to think that for certain kinds of service measuring the current on a one-minute peak is more equitable than measuring it on any of the longer periods.

I want to say something about this matter of load factor. The writer of the last paper definitely told us exactly what he means by load factor, so that when we study his paper we have right before us what he means by the term "load factor," as he uses it. He is much more considerate in that regard than many other writers, because many writers use the term "load factor," and do not give data by which one can tell what they are talking about. Load factor, I believe, should be taken as the function of the load, and as having nothing to do with the size of the plant; in other words, I believe the definition of load factor as given us in the paper by Warren and Biesecker is not the proper basis for true load factor. I believe the proper basis for load factor is the

ratio of the average kilowatts during a given time to the kilowatts integrated through some definite shorter period; that may be one minute, 5 minutes, 10 minutes, 15 minutes, or any other period of time. It is the average for the whole length of time to the integrated value for the shorter length of time that should constitute the proper definition of load factor.

Then, again, the duration of the whole period is not necessarily restricted to 24 hours. We may have daily, weekly, monthly or yearly load factors and in general the longer the period the lower will be the load factor.

C. W. PenDell: This one-minute peak that Mr. Lincoln speaks of is more or less in the nature of an instantaneous peak. I threshed over in our company the question of how long a period we should take for the peak, and on our general power we adopted thirty minutes, for this reason: In studying a customer's load we say it will take 500 kw. to handle his entire requirements, that is, 500 kw. for the transformers. These transformers will stand considerable overload for a few minutes without damage. Our lines will stand the same overload. The generators will stand it. If we take a short duration peak period, the starting up of the factory in the morning, especially if there are a number of large motors, will have a tendency to boost the customer's peak beyond where we want it to go. We do not want the rates on paper to look excessively low. We would rather keep the rates so that they look reasonable on paper, and yet have the customer earn a low rate by having a maximum demand which is low, rather than to give him a one-minute peak which will make his maximum demand quite high, and charge him a relatively low rate for the maximum.

As the chairman has said, we can hardly blame the operators of the mines for not buying power when they find that we have all these different rates to offer. There is one thing that the power salesman must get the first thing when he goes out—that is the confidence of his prospect. The salesman must have faith in the commodity he is trying to sell the prospect, and he must know that when he figures out a rate for his prospect that the rate is right. On the other hand, we must also imbue the prospect with faith in the company, that he will secure equitable and just treatment.

The central station should not, according to my theory, sell at so much a unit output of the customer, because in so doing we are taking all the risk of inefficiency in the customer's operation. You go to one man and say "I will give you current for so much a ton of coal mined," and you to go the next man and try to figure his cost and say "I will give you current for so much per ton of coal mined", these two men get together, and then the second fellow says, "Here, you are charging me 30 per cent more than you are charging the other fellow, what right have you to do that?" We try to explain to him that his method of operation is not the same as that of the other man, but you cannot explain

that to him. He has you, because he knows more about the coal mining business than you do, certainly more than I do, because I have not been in the business long enough, but if I tell them both "I am giving you the same rate per kw-hr.," and it is up to them to earn the same rate per ton mined if they can, they cannot accuse us of injustice, as they are liable to do if we try to sell them on the unit basis of output.

Sidney G. Vigo: The question of load factor is not only of extreme interest to the central station company, but also to the customer as well. The formation of rate schedules is for the purpose of giving to the customer a lower rate, corresponding to the increased hours of use of his maximum demand over any month. A customer operating twenty four hours a day naturally should receive a better rate than an eight-hour user. The schedules of rates that are designed, therefore, are inherently based on this idea of load factor.

It can be readily seen that if load factor were defined as the percentage of the actual consumption divided by the total horse power in motors installed, over 720 hours per month, that the customer would be given a higher rate than if the load factor were the percentage of the actual consumption divided by the maximum demand, over a period of 720 hours per month.

This is made all the more evident in some central stations in the Northwest, where the rate per kilowatt hour is each month based on the load factor existing during that month. At the end of each month, the maximum demand, having been measured, and the consumption being obtained, the load factor for that month is determined, and the corresponding rate for that load factor is applied, and with each decrease in load factor, the rate is correspondingly increased. Therefore, with this schedule, if instead of measuring the customers' maximum demand, the total motors installed were considered, the customer's load factor would show a decrease, and he would pay correspondingly higher for his service.

This idea of actually measuring the highest demand of any customer is urgent oftentimes, because it is found that installations in large numbers of cases are made with the idea of future development, which we all admit is bad policy, owing to the inefficiency of the operation of large units underloaded, and consequently, a customer would be paying an unfair rate for service if his load factor were based on the size of his installation, rather than on his actual conditions. There are numbers of such cases that have come to the speaker's personal attention, but there is no doubt that many of you have experienced the same difficulties.

C. I. Weaver: There has been considerable discussion about the duration of the maximum demand; whether the integrated peak should be for a period of one minute, 5 minutes, 15 minutes or 30 minutes. This diversity of opinion led to the remark that the rate for power to the coal mine should be based on ton-

nage. The tonnage basis of rates is, in my opinion, very unsatisfactory. A comparison of the rates on the one-minute period, the 5-minute period, the 15-minute period, and the 30-minute period, would show the net power bills to be approximately the same for any given load.

Different lengths of periods for maximum demand readings are the results of different conditions in the central stations and widely varying opinions of rate makers.

It is not difficult, however, to estimate the cost per ton of coal from a rate having a demand charge and an energy charge. It would be discriminatory to base power bills on tonnage since the kilowatt hour per ton varies widely in different mines.

Our organization has for a few years been marketing power to mines with a rate based on 15-minute demand with additional charge for energy. It has proved fair to the station and satisfactory to the mine operator. The field of our activities has extended into Illinois, Indiana, and Michigan.

T. E. Tynes: I wish to supplement Mr. Lincoln's remarks and the gentleman preceding, in regard to the load factor. I agree with them that the load factor is a function of the load and not of the installed capacity. I know of a certain plant in which, if the load factor was based on the ratio of the average installed capacity, it would be somewhere around 15 per cent, but based on the ratio of the average to the maximum demand, it is around 70 per cent.

I ask Mr. PenDell what method they use for integrating their 5-minute, 15-minute, 30-minute, and one-hour peak. In the company we take power from we used to measure the peak on a graphic instrument, a clear one-minute peak, and they had been working on that system for two or three years before going on the regular maximum demand meter, but finally did it, and that integrates the entire peak. We find that it raised our maximum demand from 8 to 14 per cent, depending on the nature of theload. We had to get busy to counteract that, and by generating our own power we brought our peak up to 93.1 per cent.

C. W. PenDell: In connection with the matter of measuring the peak, there has been developed in Chicago a meter for stamping the registrations of an integrating wattmeter. The train of gears on any standard wattmeter is replaced with another set of dials which have numbers on them. There is a tape which runs over the numbered dials, and a typewriter ribbon is placed in between. There is a clock which is set for 5-minute, 15-minute or 30-minute intervals and as the contact maker goes around, it stamps the registration of the wattmeter dials, the same as if a man were standing in front of the meter and reading the integrating meter at stated intervals, only the clock does it automatically.

We used to have graphic wattmeters on certain loads. I found there was liable to be a discussion whenever it came time to decide on what the maximum demand had been. Every tenth

of an inch that the customer's engineer could screw me down on the curve meant anywhere from $100 to $1,000 to him, and I did not like to have him perhaps accuse me of trying to slide up a tenth of an inch, to make $1,000 for the company, so that I took them out and put in the other meter.

George H. Morse: Recently in connection with some properties in Minneapolis, I had occasion to study the conditions with reference to load factor as interpreted by the company. There we were using the actual maximum demands of consumers as registered on the Wright demand meter, the ratio of the average load being taken for the monthly load factor—that was all right in cases where we had non-inductive loads. Where we had an inductive load, as induction motors, in order to get the maximum demand in kilowatts, we were sending out men to make actual measurements on the customers' premises with wattmeters at such times as we thought we would strike the maximum for the month, and in this connection I will say that the man in charge of the meter department has a tradition that there is a certain company in the city there, a manufacturing company, that pays one man to sit at the door throughout the month and look for the man who comes to take that maximum demand—it is his conviction that, when he sees the meter man coming in the distance, he runs through the factory and gives a general alarm to the men at work, and the machines are drawn off throughout the factory.

That company was experimenting with the maxicator or printometer the gentleman refers to, an instrument for registering on tape the wattmeter readings. That instrument is the only instrument we can apply today to inductive loads to get the maximum demand kilowatt. The Wright demand meter is not of assistance in this case, because that registers the maximum current. That is what I want to emphasize and the reason that I rose. To my thinking it is not the maximum kilowatts that we ought to base our rates on, but the maximum current, after all, even in the case of inductive load, because we have to hold in our power station capacity for that maximum current, not maximum kilowatts.

C. W. PenDell: I am having carried on now some experiments on the measurement of maximum demand of inductive loads with the Wright demand meter. I believe there is some general ratio between the power factor and the maximum load of average size commercial customers. I want to put in the Wright demand meter, if possible, on a lot of these customers, to see if I can find a ratio between the power factor and the maximum.

Relative to charging customers for maximum current rather than maximum kilowatt, in our company all generators are purchased on a 75 per cent power factor basis. We put a 750-kv-a. generator—taking that as a unit—on a 500-kw. turbine, a 7500-kv-a. generator on a 5000-kw. turbine, taking fair care of the wattless current in that way.

Our operating department is trying to get the contract department to get our customers to put in synchronous machinery, so as to cut down the wattless current. We have taken the stand that we will not needlessly complicate customers' installations to correct the company's power factor for two reasons: Whenever you get the customer to install expensive synchronous machinery to correct the company's power factor, they want a special rate, and special rates are something that we fight shy of. Another thing about the correction is, when you want the correction for power factor on your line the customer will have some reason for shutting down the synchronous machinery. You go to figuring on it, and the first thing you know he balls you up by not running it. I have told the operating department if they want power factor correction to put it in their substations.

H. M. Warren: While the tests which we ran on these substations were primarily for our own particular benefit, the results of these tests were urgently sought by a number of our companies, and I feel that with the data which were obtained and are available the central station man has all the information which is necessary, and a great deal more than he would have if he simply knew what the load factor was as outlined by the gentleman who has just spoken. One of the gentlemen stated that load factor was a definite term, comprising the average load, but from the discussion which followed I do not think it is. I have not been able to determine whether it should be based on instantaneous peak or on any peak up to thirty minutes. Therefore, it would seem to me that when the term "load factor" is used, it is necessary to qualify it by a statement explaining just exactly what is meant, in a manner similar to that which has been done in this particular paper.

A paper presented at the Pittsburgh Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 19, 1913.

Copyright 1913. By A.I.E.E.

MINING LOADS FOR CENTRAL STATIONS

BY WILFRED SYKES AND GRAHAM BRIGHT

The most desirable type of load that a central station can obtain is one which has both a high load factor and high power factor. Load factor is, generally, defined as the ratio of the average load of a machine, or system, to the rated capacity. Capacity is, sometimes, based on the name plate rating, but, for the purpose of obtaining load factor, it should be based on some integrated time peak, that represents the capacity which the central station must provide, and hold in readiness for the use of the customer.

The load of a mine operation, taking power from a central station, consists, in general, of the following: Haulage, Hoisting, Ventilation, Coal Cutting, Pumping, Tipple or Breaker Power, Machine Shop and Blacksmith Shop, Lights.

Haulage. The load due to a haulage system, is, as a rule, very ragged; the variation depending upon the number of locomotives operating and the grade conditions. Figs. 1 and 2 are typical, and show the wide variation in load that takes place in short intervals of time. Unless the power system has a rather small capacity, this variable load will not seriously affect the regulation for power loads, but may give unsatisfactory regulation for lighting.

In practically all cases in this country, the power used for mine haulage is direct current, either 250 or 500 volts. With purchased power, the current is obtained either from synchronous converters or motor-generator sets. The motor-generator sets may be either induction or synchronous. When there are very few locomotives in use the d-c. generator must be able to stand very heavy overloads, for short periods, so that the actual capacity is often determined by the ability to carry heavy mo-

mentary overloads, rather than the continuous heating capacity. When this peak load is the determining factor, it is possible to supply a driving motor smaller than the generator, provided the motor has ample pull-out torque. The efficiency and first cost would be improved, when using such a motor, and also the power factor, if the motor is of the induction type. This scheme is particularly applicable to the case when old types of generators are at present driven by steam engines and it is desirable to change to motor drive. In many cases, these old generators will stand very little overload, due to poor commutation, and seldom receive overloads, due to the inability of the engines to stand much more than full load without becoming stalled. Instances have occurred when a 200-h.p. motor was ample to drive a 200-kw. generator. Fig. 2 illustrates a load of this

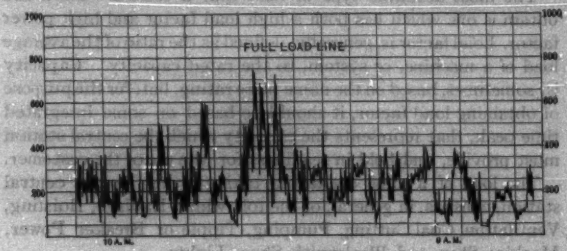


FIG. 1—DAY LOAD ON 800-AMPERE MINE PLANT

character. Where the capacity is not determined by the peak load, it should be determined by the r. m. s. rather than the average kw., for both motor and generator, since the heating for such a variable load will be considerably greater than that due to the average load. This point is well illustrated by Figs. 1 and 2.

The load factor of the haulage system will not, as a rule, be high, but can be improved in some cases by a careful study of the schedules on which the trips are brought to the surface.

The effect of the haulage load on the power factor of the system depends upon whether synchronous converters, induction motor-generator sets, or synchronous motor-generator sets are used.

With the induction motor-generator set the power factor will depend on the load, and will not average very high, due to the fact that the average mine load is low. The synchronous con-

verter will have 100 per cent power factor at full load, and can be made to give a slightly leading power factor at lighter loads. The synchronous motor-generator set has somewhat better characteristics than the synchronous converter, and is better adapted for mine service, due to the superior compounding characteristics of the generator. Heavy compounding is very desirable for mine service, especially when the voltage is 250. The high power factor of the converter or synchronous motor-generator set will, of course, tend to compensate for the lower power factor of the fan, hoist, and tipple motors.

From a standpoint of cost, the desirability of the various types of apparatus for converting a-c. power to direct current is in the following order:

1. Synchronous converter

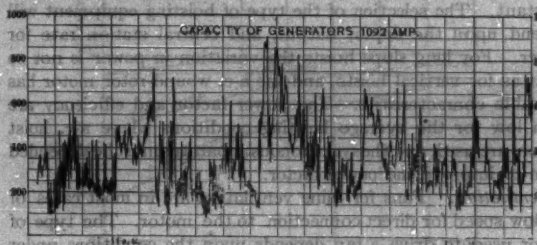


FIG. 2—DAY LOAD ON 1092-AMPERE MINE PLANT

2. Induction motor-generator set
3. Synchronous " " "

From a standpoint of best operating conditions, the desirability is as follows:

1. Induction motor-generator set
2. Synchronous " " "
3. Synchronous converter.

From a standpoint of power factor correction, the desirability will be as follows:

1. Synchronous motor-generator set
2. Synchronous converter
3. Induction motor-generator set.

Hoisting. In mines where hoisting is necessary, the load factor depends upon the nature of the hoist. Where the shaft is

vertical, and high speed and frequent hoisting is required, the load curve covers a wide range in a few seconds of time. The momentary peaks are very high, while any integrated time peak of one minute, or more, will be fairly low.

This type of load will often cause poor regulation on a power company's system, and is not, as a rule, a desirable load. However, if there is considerable haulage, fan, pump, and cutting load at the same time, the high peaks will be somewhat smoothed out.

Where the peaks are excessive, and cause bad regulation, some method of equalizing the load is used. The best known of these systems is the Ilgner, which employs a separately excited hoist motor, receiving power from a separately excited generator driven by an induction motor. By means of a flywheel, and slip regulator, the load on the power system will be practically constant. The selection of the type of hoisting equipment will depend upon the depth, output, and central station rate for power. For long slope hoists the variation in power is not so great as for vertical hoists, and the a-c. wound-rotor motor has desirable characteristics. The power factor and efficiency are both low for the average hoisting conditions where a-c. hoist motors are used, and the synchronous apparatus must be depended upon to improve the power factor.

Ventilation. Fans for mine ventilation are in most cases of too low speed for direct connection to the motor. The type of motor used to drive a fan depends upon the conditions under which the fan is to operate.

When the fan operates at the same speed 24 hours per day, and is changed only at intervals of a few months, to take care of the mine development, a simple arrangement is to belt a constant-speed motor to the fan, and change pulleys when a change in speed is desired. The simplest type that can be used for this application is the a-c. polyphase squirrel cage motor. When this motor is to run at low load for long periods the power factor can be improved by a special winding. In some cases it is desired to operate a fan at a certain speed most of the time, and, occasionally, at a somewhat higher speed for emergency conditions. A simple method of accomplishing this is to supply a double pulley, and change the speed by sliding the belt from one pulley to the other. Since the motor is to be operated at a reduced capacity a large percentage of the time, it would be desirable to have a high power factor and high efficiency at light load. Fig. 3

illustrates what can be accomplished by supplying a special winding to a standard motor, to improve the power factor at light loads. The efficiency may suffer at full load, but this makes little difference, as the proportion of time that the motor operates at full load is small. The same effect can be accomplished by supplying reduced voltage taps so that the motor can be run at a lower voltage when lightly loaded.

When two definite speeds are required, these can be best obtained by the two-speed squirrel cage motor, if a-c. power is available. If d-c. power is to be adopted, the commutating pole d-c. motor can be used to give high economy at a large range in speed, by field control. Where variable speed is required for an a-c.

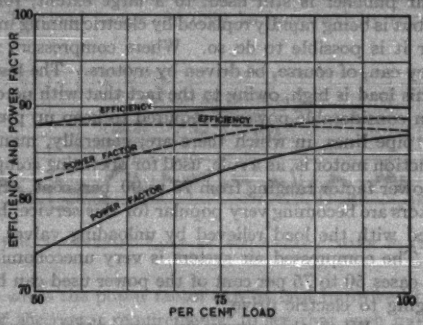


FIG. 3—PERFORMANCE CURVES OF SQUIRREL CAGE TYPE MOTOR
Full line curves are for standard windings
Dotted line curves are for special windings designed for high power factor at light loads

motor, this is generally accomplished by using a wound rotor and putting resistance in the rotor circuit. The economy is of course low at any but full speed. The fan load, being very steady, will greatly improve the load factor and regulation. The power factor will not be high, since a fan motor is seldom run at full load.

Several schemes are being tried out in Europe to give economical ranges in speed when using a-c. power, by the use of the three-phase commutator motor, and also a combination of wound-rotor induction motor with low-frequency synchronous converter and d-c. motor. While these schemes may be worked out with a fair degree of success in Europe, their success in this country remains to be seen.

Coal Cutting. The power used for coal cutting is generally direct current, and is often taken directly from the trolley system. Much better voltage regulation can be obtained, as a rule, where separate feeders are run for the cutting machines. The load factor of a single cutting machine is rather low, as it operates but 10 to 15 per cent of the time. Each operation lasts several minutes, so that the effect on regulation is not bad, and with several machines in operation, the load factor will be fairly high.

A practise which seems to be gaining favor is to do most of the cutting at night. This greatly improves the low load factor at night, and in many cases relieves the generators, which are overloaded during the day.

The air puncher is still used, to a large extent, for undercutting, but is being rapidly replaced by electric mining machines, wherever it is possible to do so. Where compressors must be used, they can, of course, be driven by motors. The load factor due to this load is high, owing to the fact that with no cutter in operation considerable power is required to keep up pressure in the long pipe lines, in which there are, generally, many leaks. The induction motor is, as a rule, used for operating compressors, with a power factor ranging from 75 to 90 per cent. Synchronous motors are becoming very popular for this service, but must be started with the load relieved by unloading valves, or bypasses. The compressed air system is very uneconomical, and in many cases 50 to 75 per cent of the power used can be saved by changing to electric drive.

Pumping. When the pumps are some distance inside the mines, direct-current motors, direct-connected to centrifugal, or geared to triplex pumps, are generally used. Power is taken from the haulage, or coal cutting lines. For large pumps, a-c. motors are used to advantage. These are, in most cases, induction motors. Where compressed air is used for punchers, it is also used, sometimes, to operate pumps and fans. Often the old steam engines are simply connected to the air system, and with the usual low air pressure and absence of pre-heating, the efficiency will, of course, be very low.

The load factor due to pumping will be very high, as a pump is usually run on constant load for hours at a time. In some mines the 24-hour load factor is very materially increased by using small pumps during the day to pump to a common reservoir or sump, and then using a large pump to raise the water out of the mine during the night. For these small pumps the

self-starting d-c. commutating-pole motor has been very favorably received by the mine operators, as it cuts down the pump attendance to a minimum.

Any scheme by which a day load can be shifted to the night turn will not only improve the load factor, but will cut down the capacity of the generating apparatus. Fig. 4 shows a typical night load, consisting mostly of cutting machines, and indicates the need of improvement of load factor.

Tipple or Breaker. Motors used on the tipple, or breaker, are generally of the induction type, squirrel cage or wound rotor. Direct-current motors are frequently used where the operation has an isolated power plant. The load factor is fairly high, but the power factor will not average high, due to the fact that many of the machines are working under-loaded at times. The load factor can only be improved by regularity of

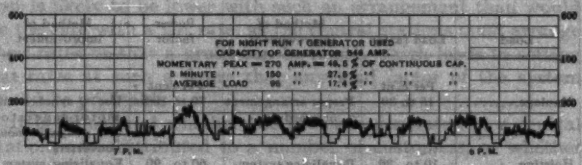


FIG. 4—EVENING LOAD ON 600-AMPERE MINE PLANT

output, while the power factor can be best improved by a close study of the power requirements, to see that each motor is of the proper capacity for the work. In some cases, by the addition of a small flywheel the capacity of the motor can be reduced, and the power factor and efficiency increased. It is for such a load as a tipple, or breaker, that power factor correction is desired, by the use of synchronous apparatus.

While making investigations, at different mines, of the power requirements, one of the authors has frequently come across steam power applications where the engine is far larger than necessary. The general reason for this is that the particular engine was the only one available at the time, and the advantage obtained was that the engine would operate for long periods with little or no attention. The difficulty of making tests on an engine is sometimes responsible for these misapplications. On the other hand, the ease with which electrical tests can be made

makes it a comparatively simple matter to select a motor of the proper capacity.

Machine and Blacksmith Shop. The machine and blacksmith load is, generally, too small to have much influence on either load factor or power factor. Direct-current or squirrel cage induction motors are used.

Lights. The lighting load is a small percentage of the total, where the lighting is confined to the tipple and mine proper. This lighting is, generally, taken from the haulage system, to save wiring. With purchased power, all outside lighting should be alternating-current, since the regulation on the haulage system is not suitable for economical lighting.

The following table shows a summary of the various load factors and power factors, and ways in which they can be improved:

Load	Load factor	Method of improvement	Power factor	Method of improvement
	Per cent		Per cent	
Haulage	15 to 30	Proper arrangement of schedule	70 to 100	Use synchronous motor-generator sets or synchronous converters
Hoisting	10 to 30	Equalizing system	60 to 90	Equalizing system
Ventilation	100		70 to 90	Use special winding to give high power factor at light loads
Coal cutting	20 to 50	Do cutting at night to improve load factor of system.	70 to 100	Use synchronous motor-generator sets or synchronous converters
Pumping	70 to 100	If possible change part of pumping to night turn	70 to 100	Use synchronous motor-generator sets or synchronous converters
Tipple or breaker	20 to 60	Keep output steady	50 to 70	Use motors of proper capacity—not too large
Machine shop	40 to 70	Load too small to affect load factor seriously		Use motors of proper capacity—not too large
Blacksmith shop				
Lights	60 to 90	Load too small to affect load factor seriously		If a-c., use transformers of proper capacity—not too large

Power Rates

The larger purchasers of power generally have a fairly good idea of how their power costs are made up, although very often

they have no definite information as to the actual costs. Most operators appreciate that their costs may be roughly divided into two groups, the first including the fixed charges, such as interest, depreciation, and amortization, and the second the various charges such as fuel, stores, labor, etc.

In a given station some of the items included under the second heading may be considered as fixed charges, as they are, practically, independent of the load. This is the case with such items as labor, line maintenance, etc.

Keeping in view the fact that the cost of power is made up of a fixed element and a variable element, it is clear to most large consumers, who have given the matter attention, that the most equitable way of charging for power is one that is based on a system that takes this into consideration.

Furthermore, they are alive to the fact that their total power cost is likely to be lower with such an arrangement than would be the case with a flat rate, as the central stations must arrange their rates so that a profit can be made, which leads to setting flat rates at such a figure that any load factor of the system would be profitable.

It is immaterial whether the power is generated in a central station, and distributed to a number of customers, or whether each of the consumers has his own generating station; the power cost will be made up of the same items, which can be very easily demonstrated to a prospective customer. The difficulty always occurs in persuading the customer that the particular rate proposed is a fair one.

Although the question of power rates is, mainly, a local one, a short discussion of various power rates, and how they may be influenced by the customer's load, may not be out of place.

Flat Rate. Very little power is sold to large users on a flat rate. On account of the simplicity of this system, it is very suitable for small customers, where it is impossible to obtain an intelligent appreciation of the proper basis for charging for power. Flat rates are usually very high, and necessarily leave a considerable margin for variation of load factor.

When power is to be purchased in large quantities, a flat rate does not enable the customer to obtain the advantage that should be derived from high load factor, or, if it is so arranged as to do this, it does not adequately protect the central station. This system is therefore quite unsuitable for large customers, and can only be defended on account of its simplicity, and the difficulty

that is encountered in properly determining the basis of an equitable power charge.

Maximum Demand System. The late Dr. John Hopkinson suggested this system over twenty years ago, the idea being to take the load factor into consideration when determining the power costs. This system, as worked out by various companies, principally in England, of recording the maximum instantaneous demand, and basing the power costs upon one rate for a certain number of kw-hr. per month per kw. demand, and upon another rate for the remainder of the power, has been generally known as the Wright system, from its principal advocate, Mr. Arthur Wright, who introduced it many years ago.

For instance, for the first 50 kw-hr. per month per kw. demand the rate might be five cents, and for all power in excess the rate of, say, one cent might be charged. Thus, if the maximum demand is 100 kw., and the monthly power consumed is 10,000 kw-hr., the first 5000 kw-hr. would be charged at five cents, and the second 5000 kw-hr. at one cent, making a total of $300, or an average rate of three cents. This system has been used in various forms, and is still used by a number of concerns.

For industrial power it has a great many disadvantages, not the least being the difficulty of determining the maximum demand. The system is not on the correct basis, as it does not take into consideration the equipment that the power station must have available for the customer. It is, however, a decided improvement upon the flat rate system, but a poor system to use with small customers, in view of the difficulty of explaining the great variation in the cost of power that is liable to occur at different seasons of the year. This difficulty is increased in proportion to the number of customers on the system. With a few large customers there is usually very little trouble in adjusting the accounts, and explaining the variations.

Due to the fact that it does not clearly recognize the basis on which the cost of power is founded, it is not an easy rate to explain to a customer. There are a number of variations which attempt to avoid the defects of this system. For instance, a certain percentage, only, of the maximum peak is sometimes taken as a basis of charging, but the system is fundamentally wrong.

Flat Rate with Fixed Charge. In view of what has been said as to the cost of power, it is obvious that the only correct basis is one that takes into consideration the fixed charges

on the equipment that must be kept in reserve for the customer, and a variable charge depending on the amount of power consumed.

The only way that the amount of power station equipment that is required by each customer can be determined is by keeping some record of the customer's load conditions.

There are certain differences of opinion as to what is a fair basis on which to determine fixed charge. Some operators are of the opinion that any load that may be sustained for a period of, say, five minutes, is the proper basis, and others take into consideration the average load for some definite period. The latter is, in our opinion, the correct system, especially for mining work, or for any service where the load fluctuates very rapidly. For instance, if the five-minute peak load is to be taken as the basis for fixed charges, it is quite possible to have such conditions that there never will be any peak that will last this time. It has been our experience that there is quite a number of cases where a strict reading of the contract would mean that the power company could not collect any sum for fixed charges. Then, again, within certain limits, the instantaneous peak loads do not concern the central station, as the generators have sufficient overload capacity to take care of such peaks.

It is the load that must be carried for, say, fifteen minutes, or half an hour, that really determines the capacity of the generating plant, and therefore the proper basis for charging is one that takes this point into consideration. In other words, the average, or integrated, peak load, for a reasonable period, must be used. The period taken is, generally, fifteen minutes to half an hour; the larger power stations adopting a longer period, as the variety of their load enables them to take a more liberal attitude towards the customer than is possible with a smaller station.

To determine, to some extent, the effect of the length of the integrated peak upon the basis of charging, a number of investigations have been made, and the results of one case are shown in Fig. 5. This figure shows the peak load on a basis of a 5-minute, 10-minute and 15-minute average peak. The results may be summarized as follows. Taking the 15-minute peak as a basis, the 5-minute and 10-minute peaks are given as a percentage:

15-minute peak	100 per cent
10- " "	104 per cent
5- " "	106¼ per cent

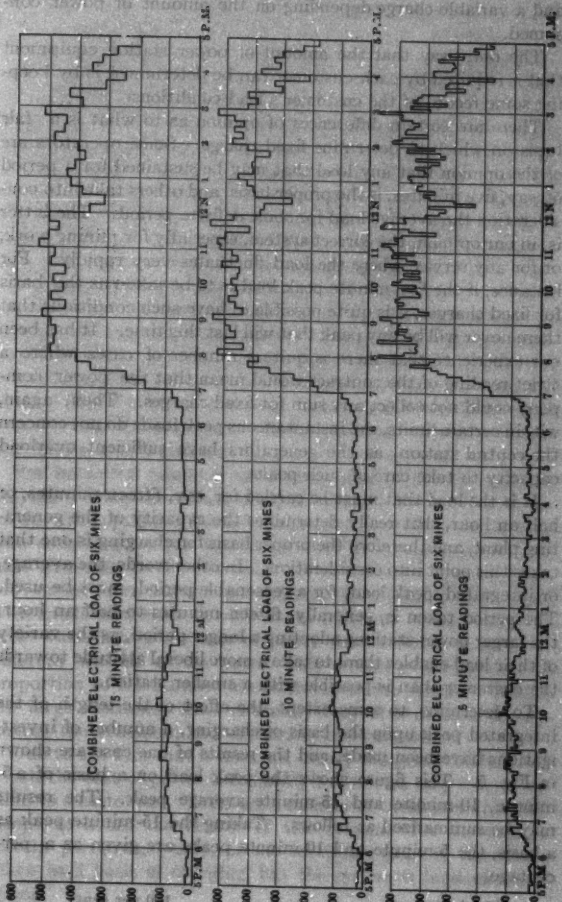

COMBINED ELECTRICAL LOAD OF SIX MINES
15 MINUTE READINGS
COMBINED ELECTRICAL LOAD OF SIX MINES
10 MINUTE READINGS
COMBINED ELECTRICAL LOAD OF SIX MINES
5 MINUTE READINGS
600
500
400
300
200
100
0
6 P.M.
7
8
9
10
11
12 M.
1
2
3
4
5
6 P.M.

FIG. 5

The difference is comparatively small, and it is generally easier to persuade a customer that a 15-minute peak is an equitable basis, which is not always the case with a 5-minute peak. The results shown in Fig. 5 are made up of simultaneous tests, made on six different mines belonging to one company.

It is usually not possible to arrange the fixed charge that a large customer pays so that it will cover the total fixed charges of the station that would be represented by the capacity measured on, say, a 15-minute integrated peak, as the charge would be so high that it would be difficult to secure business.

It is usually very easy, however, to obtain a fixed charge that would be equal to the corresponding figure if the customer installed his own station, which he could do, generally, at a lower cost per kw. capacity than the central station, as he would have considerably shorter lines, and the standard of equipment probably would not be so high.

It is, therefore, generally necessary to take a figure somewhat lower than the full amount, and from the standpoint of the central station this is justified, because the central station obtains the benefit of the diversity factor, which under certain conditions may be considerable.

This may be illustrated in the case of the diagram shown in Fig. 5. The total 5-minute peak of the six mines is only 68 per cent of the sum of the individual 5-minute peaks of the different mines. The diversity factor, in this case, is 1.46 to 1. Where many mines are being operated from one station a much greater diversity would be expected.

The additional flat rate per kw-hr. is a very much more flexible charge, and the average customer is usually prepared to stand for a flat rate that represents a fair profit, whereas the fixed charge must be reduced below what is really an equitable figure. A great deal of this difficulty is due to the fact that customers have, as a rule, very little idea as to the proportion of fixed and variable charges in their power accounts, and therefore have not been educated to see these charges in the proper relation.

In the case of a large system, supplying power to both large and small consumers, the question naturally arises, should the large user pay the same rate as the smaller one? In general, it is reasonable for the large customer to expect a lower rate, as he looks on the matter from the standpoint of what he could do with his own generating plant, and this is a condition that must be met by the central station.

The cost to a station decreases, somewhat, as the amount of power used increases, as the expenditure for lines, labor, etc., for the equipment required by any one customer is not very different whether the average load is 100 kw. or 1000 kw. A system of giving a discount on the rate per kw-hr., depending upon the consumption, would be a fair and equitable method of meeting this condition.

Effect of Power Factor on Rates. This is a question that is of considerable interest to the central station. Usually, no difficulty is encountered in demonstrating to a consumer that a reasonable power factor should be maintained. Some central stations are attempting to meet this condition by regulations designed to control the type of apparatus used by the customer, but there are limits to this arrangement that reduce the value of the scheme. It is customary to require synchronous motor-generator sets to be used for direct-current work, and, as a great deal of the power required by mines is for haulage, coal cutters, etc., fairly good results can be obtained by this simple expedient, but there are a great many cases where induction load predominates, and a more definite scheme is required. It appears to the authors that, if it is found necessary seriously to consider the power factor, a definite limit should be set, and for lower values an increased rate charged. This can be arranged for by determining the kv-a. and kw. consumption of the consumer. To make it desirable for the customer to maintain his power factor as high as possible, a bonus might be given if it averages above the limit set.

Methods of Measurement. Although some system based upon the peak loads is generally recognized as being correct, it is not at all easy to determine a rate with a basis that can be accurately measured, due to the fact that in the past, apparatus has not been available for the satisfactory recording of the peak loads. Graphic recording meters of the usual type are not at all satisfactory, as they do not show the maximum average for a definite period, without a considerable amount of investigation, and they are not accurate if used to record the instantaneous peaks.

When rates are based upon the instantaneous peak, a certain percentage of which is taken to represent the station capacity required by a particular customer, there is, usually, room for considerable discussion as to the methods of determining these peaks.

During some investigations made by one of the authors on the high cost of power for a particular installation, it was found that the meters used, under certain conditions, recorded peaks approximately 60 per cent above the actual value, due to the meters overshooting. This discovery led to a further investigation of a number of other installations, and it was discovered that a similar condition existed, which caused considerable dissatisfaction on the part of the customers.

The graphic meter has the advantage of giving a chart that is a permanent record, which can be used in case of disputes, and it shows extraordinary peak loads, due to short circuits, etc., which can be left out of consideration in determining charges.

The type of meter that simply indicates the maximum instantaneous peaks, has the disadvantage that it does not discriminate between peaks due to short circuits, and normal operating peaks, so that such instruments are practically useless, under modern conditions, for industrial plants.

Undoubtedly the proper instrument to use is a meter that will integrate the peak load for a certain definite period, and record this in such a way that the values may be referred to, at any time, in case of dispute. Such instruments have been devised, and we believe that the first were designed about six years ago for the Victoria Falls Power Company.

Due to the fact that the question of power rates has not been given the consideration that it deserves, such devices have not been developed to the extent that would be desirable, through a lack of demand on the part of the operators. During the last few years, however, the increased effort on the part of central stations to secure industrial loads has increased the number of large consumers, and has brought this question of charging to such a position that these devices are receiving more attention. In designing such apparatus provision must be made so that the meter will pick out the highest peak. For instance, if a 15-minute peak is the basis of charging, it would not be satisfactory to simply have a meter divide the hour into four parts, as it may happen that a high peak might be then divided into two parts, part occurring during one of the periods, and part during another. If a peak load of 15 minutes' duration occurs, and it should happen that it starts in the middle of one of the periods, the maximum recorded by the meter would be only half the correct value. If two integrating devices are used, both operating on the same recording device, and they are staggered, then there

is no chance of such a condition occurring. It may happen that the record will not show the absolute maximum, but the difference will be very small.

Power Factor Measurement. The power factor must be considered in conjunction with the power requirements, and any scheme using a graphic power factor meter is unsatisfactory, as it might easily happen that for fairly long periods a leading component is provided by the motor-generator, which would be of little value to the station, as it would not exist during the time when the equipment is loaded to its capacity. A much more satisfactory system is to consider the average power factor, but it is not possible to obtain values direct, as no kilovolt-ampere meter is available. We can, however, integrate the wattless component by a suitable meter, and thereby obtain the average value of power factor.

Suggestions for Power Contracts. In view of what has been said, we would suggest that an ideal power contract for mines should be based upon the following:

(a) Fixed charge, depending upon the integrated peak load for a reasonable period, so that it will represent, approximately, the equipment required to carry consumer's load.

(b) In addition to the above, a flat rate per kw-hr., based on operating costs, taking into consideration the amount of power used, and allowing a graduated discount to give large consumers a lower rate.

(c) If power factor is a consideration, a reasonable limit should be set, lower power factors being penalized by increasing the rate per kw-hr., and a reduction in rate granted if high power factor is obtained.

We believe that if this plan were generally followed, it would be possible to meet all the conditions arising in mining work, and to fix rates that can be given to all consumers that will represent profitable business.

In conclusion, it must be pointed out that to secure this load the central station should adopt a generous policy towards its customers, and when there is doubt as to the effect of operating conditions upon the station's costs, it should be prepared to accept the risk, rather than attempt to place a burden upon the consumer which may not be justified by results. The central station has the advantage of the diversity of loads, and a part of this benefit should be given to the consumer.

DISCUSSION ON "MINING LOADS FOR CENTRAL STATIONS" (SYKES AND BRIGHT), PITTSBURGH, PA., APRIL 19, 1913.

P. M. Lincoln: I do not think in our industry there is anything on which the members of the fraternity have more divergent opinions than they have on this question of power rate. It is somewhat difficult in the first place to obtain a proper conception of the items to include, to arrive at a proper power rate. Possibly the best way to get at it would be to consider the things which go to make up the ideal power rate. In starting out on this task it is very possible, in fact it is almost certain, that what may be an ideal power rate in my opinion may not be an ideal power rate in the opinion of some one else.

In my opinion the ideal power rate should recognize load factor, it should recognize the power factor, it should recognize the quantity of power, and it should recognize the time of day at which the peak load occurs. In addition to these requirements, it should be easily measured, and measured by standard instruments one can get on the market, and by instruments which do not have an excessive cost. In addition to all that, it should be a rate which is easily explained to the customer.

When you have got that far, you can see that there are some inconsistencies, among the items that go to make up the ideal rate, because a rate which takes into consideration load factor, power factor, quantity of power consumed, and the time of day at which the peak occurs, is not easily measurable and also is not one which will be easily explained to the power customer.

We are, therefore, forced to the proposition of selecting a rate which will give the best compromise, and just what that compromise shall consist of is the point on which most us will differ.

The rate which has been suggested in the paper is, I think, an equitable one. It depends upon the maximum demand plus a kw-hr. rate, and a suggestion is made that the power factor should be taken into consideration, but just how that is going to be accomplished is not disclosed. I believe that a rate that is based upon the suggested method of measuring is an equitable one. However, the question of measurement is a difficult one. There are instruments on the market which will measure maximum demand, but they are not cheap, and as yet they have not had a very wide application, so that here again is a serious difficulty that confronts us when we come to this question of power rates. The demand for some instrument which will give us the maximum demand and possibly also take into consideration the power factor, will eventually result in the production of a meter which will be cheap and accurate, and will be standardized, but as yet I do not believe that we can now say that we have such an instrument.

Sidney G. Vigo: In the paper by Messrs. Sykes and Bright, on page 1136, under (b) the statement is made: "In addition to the above, a flat rate per kw-hr., based on operating costs, taking

into consideration the amounts of power used, and allowing a graduated discount to give large consumers a lower rate." I believe that this basis of charge is considered very carefully in Mr. Hopkinson's design of his wholesale rate of charge, of which he speaks in the early part of his paper, that is, based on a kilowatt demand charged for fixed investment, and a sliding scale for the operating charges or the kilowatt-hours consumed per month.

Along these lines various central stations in the country have based a secondary charge, as it is called, per kilowatt-hour consumed, on such a sliding scale as ranges down. If a mine consumes, say 50,000 kw-hr., it gets a rate which runs down until it strikes about 6 or 7 mills per kw-hr. and below this sliding scale rate there is a still further discount given for prompt payment of bills.

Now, the central station, in addition to offering a rate of this kind, should take into consideration, as Mr. Lincoln suggested, the time at which the peak comes during the month. Where the central station is located in a large community, where it has considerable general business, and the business of the mine is only incidental to its general business, it may be considered that the mining operation is primarily off-peak business. They consequently should rectify their primary charge, or fixed investment charge, to conform to the investment required for the mine, which keeps off its peak. This should involve a different rate from that which is offered to the ordinary consumers, and the central station should be in a position to offer a very flattering rate to mine operators.

The matter of peak we know is of considerable importance to a central station company, not only during the summer months when the mine operates, but speaking of it in a general way. It might be shown that in one of the largest central stations, probably the largest, in the middle west, there are investments of $80,000,000 in equipment, transmission lines, etc., and during the summer months $25,000,000 of that investment is lying idle, and this large amount of equipment is installed to take care of the peak in the winter months; consequently, it has arranged very flattering off-peak rates to all classes of industries in order to improve its yearly load factor.

There is one point which Mr. Bright touched on in reading the paper, in the early part of it, which did not deal with the rate situation, but was a question of operating steam engines in mines. The fact that the engine was considerably larger than was required was due to the fact that there was no other engine available. That is quite a common occurrence in mines, as well as a matter of fact, in all classes of business, and it brings out very forcibly one of the strongest points that central station companies could use as arguments in favor of their service, and that is the flexibility of central station drive. As the mine will increase in capacity, or other machines are added to its equipment, it is not necessary to put in a larger unit—simply add

a larger motor; and in view of the contemplated growth of a mine, it is sometimes customary to put in a considerably larger engine than is required at the outset, and you can see that in this way the inefficiency at which a plant was operated during the earlier period might be quite considerable.

The central station company, although it is not its inclination to curtail the activity of the consulting engineers, maintains men who are thoroughly familiar with all classes of industries. The central station will have a man for instance, who will be an expert on mining, and he will give every attention possible not only to the securing of the business but also to the designing of the best equipment for the mine, and one of the prime slogans, you might say, of central station activity is the fact that after the piece of business is secured the work of the power man has only just begun. He must necessarily follow this piece of business and see that it continues to operate to the satisfaction of the consumer, and he should always be ready to offer any suggestion that will improve the economy of the operation.

Theodore Swann: I am connected with a company in West Virginia which is installing a plant in the heart of the coal fields, with the express idea of serving the coal mine load only. We tried to determine that ideal rate, which I know we have not done so far, but we have given the customers a certain benefit of the diversity. If a customer's demand is between 50 kw. and 300 kw., we determine his demand on the basis of a five-minute integrated peak, and set his circuit-breaker at 100 per cent overload, thus giving the individual mine the benefit of a 100 per cent overload, which will take care of any drop. If the demand is between 300 and 500 kw., if there is more than one line being operated by this customer, because there are very few individual mines that require over 300 kw., we lengthen the time out to 10 minutes, and only give him 75 per cent overload, instead of 100 per cent overload. In the case of a customer using 500 kw. and over, we stretch the time to 15 minutes, and cut the overload down to 50 per cent. In that way we believe we have every class of customer paying us the same interest charge. By actual investigation of more than one hundred plants in the field, we find the average investment per kw. of station capacity by the customer to be $80. If we charge six per cent interest on that, and 7.5 per cent for obsolescence, as we prefer to call it, and 1.5 per cent for insurance and taxes, we have a total of 15 per cent fixed charges per kw. of rated capacity, which makes a rate of $12 per year for fixed charges, independent of operating expenses, and we determine our rate on the same basis at $12 per kw. of demand per year, to cover the carrying of reserved capacity for the operator. On tests made on fifty-six plants, which will average 200 kw. each, we found the integrated peak to be 60 per cent of the installed capacity, and that means the customers would be paying themselves on the basis of $12 per kw. per year, but on the same number of kilowatts, only paying

us 60 per cent of that. They would have the 40 per cent, which means that is the reserve carried over the average of the fifty-six plants that we have tested on this basis.

As to the load factor, we found the minimum load factor based on the integrated peak to be 5.3 per cent, and the maximum load factor to be 49.7, and the average of the entire field to be 26.4, but the load factor based on demand to be only 15.8 per cent. These figures were determined by the printometer which we used on all the plants, conducting tests which covered from one day to ten days, in securing the average. We determined the average tonnage by the production for 1912, and during the time of all these tests we were "off" less than one per cent of the average normal production, so for that reason the figures may be taken as representing actual operating conditions to a degree which is measurably correct.

As to the diversity, by plotting the load curves of twelve plants we found the diversity to be 14.25, and taking twenty-two plants we found a diversity of 1.52. We figured originally we would have a diversity of 1.5, and instead of receiving $12 per kw. per year of demand we would receive $18 per kw. of our central station demand, thus enabling us to put more money than $80 per kw. including transmission, into our service.

From the present test, it would seem that our 1.5 diversity is going to be low. The 1.52 was based on the average of twenty-two plants, that aggregated 3,000 kw. of demand, and we expect to have on our line something like 20,000 or 25,000 kw. so that it would indicate, while the ratio is very much less as you increase the number of plants, that it will be possible to obtain a diversity, an hourly mining load, of at least 1.75. That is on bituminous coal, the majority of the mines being drift or slope mines, only about 10 per cent of our total output being shaft mines, and in that particular instance we measured the current to the customer at one point, and he carried it out to 18 points, so they get the benefit of the diversity before it goes on our line. If we had more of the hoisting loads, as you have in Pennsylvania, I do not think we could get the same results we had on that basis.

One of the most advantageous features to the mine operator in purchasing power, in my opinion, is to have a definite method of determining his cost. I have made the statement to some operators that we might charge them 25 per cent more per kilowatt-hour for current, and even at that we would save them money at the end of the year. At first that sounds more or less like a fish story, but relocation is our one hobby. The average power plant will lose from 30 to 50 volts in transmission from the power house to the drift mouth. In no case have we recommended underground substations. We want to simplify the operation in every way possible. This relocation means additional voltage on the machines; and in the case of one mine, which represented an average condition, which we tested, we

found that by improving the voltage, due to the bonding, they could haul twenty cars per trip in lieu of twelve cars. This condition in that mine was more of an average condition, rather than an abnormal condition. We have made the statement, and we have proved it out in actual test, that two locomotives or two mining machines will haul more coal and cut more coal than three locomotives and three mining machines, if you give the two locomotives and two mining machines good voltage and give the three locomotives and three mining machines ordinary voltage, not taking the worst condition. We have found some mines attempting to haul coal with as low as 40 volts. It is needless to say what the results were. It appears that the average power plant was installed somewhere near water, and as the mines grew and opened up their workings it was natural that the scene of actual operation in the mines became more removed from the site of the power plant, and our idea, in going into the field of supplying power for mining operations, is that the generation of current for mine use is becoming an alternating current proposition, though its use inside the mine may be in the form of direct current.

As to a uniform contract, the first thing we decided on was that we would give an absolute uniform contract and not vary from it in the slightest particular. I am glad to say we have over half of our plants loaded, and we have not made a variation of our rate in a single contract. We at first determined the form of contract which we believed was fair and equitable, and we have stood on that contract. It is based on the $12 per kw. of demand, and in addition to that a base rate for current supplied of 1.5 cents per kw., with a discount starting at 10 per cent and going in steps of 2.5 per cent up to 55 per cent. Our current charge runs from 1.35 cents down to 6 mills, based on the quantity used. The lowest discount is given on 10,000 kw-hr. per month, and the highest on a million kw-hr. per month. We have been able on these rates to obtain three of the largest operations in the field, and a great many smaller ones, and in practically every case we were able to show that, even on our rate, which we were very frank to state to the operator is high enough, we cannot give them strictly first-class service, and it has been my experience that the operator would rather pay a reasonable rate and be guaranteed good service than to buy something cheap; in other words, we say we are selling them service, and incidentally furnishing them with power. To carry that out, I may say that all of our construction will be steel towers, the poles all on loop circuits, and there will be no mine but what we can serve from two different points, unless it is a small branch off the main line; we will use 44,000 volts for our secondary, and when we develop a waterpower plant we may use something higher.

I have found that the operators in West Virginia are not after something cheap, they are after the most reliable service which they can obtain; they are installing alternating current

and properly applying it. In nearly every case that we canvassed, the operators of the mines were more than anxious to get the facts about their equipment, and many of them said "we want you to please tell us frankly what you think of our conditions." Sometimes they have been so bad that we did not dare tell them frankly what we did think of them. I have dealt with the coal operators for about four years, and of all the different classes of people, I believe they are a class you cannot "put anything over on" and get away with it. You must have a fair, square rate, you may tell them you are charging them enough, but you must give every one of them exactly the same rate. I have known of cases where a salesman would sell one operator something at one price, and another operator the same thing at a different price, and it is only a question of days until that man's usefulness is done with in that particular field. I think that is true of the coal operators more so than it is with any other class of people. The inter-relationship and ownership between the companies makes it absolutely necessary to have a uniform contract. We have a new Public Service Commission in West Virginia, which, to a certain extent, has been the reason why we cannot make exceptions. On the other hand, when a coal operator believes he is getting the same contract as every other man, the tendency is for him not to read the contract, even. He will say, "Is this the same contract that so and so has?" And I will say, "Yes," and in some cases show the signature of the other man, and he will sign the contract and say, "If I am getting what he is getting, it is all right."

H. C. Eddy: I think that Messrs. Sykes and Bright are to be congratulated upon the many good things that appear in their paper. There is one paragraph, which I think most mine operators ought to cut out and paste somewhere where they can refer to it frequently and become thoroughly familiar with it. That paragraph is this:

"It is immaterial whether the power is generated in a central station, and distributed to a number of customers, or whether each of the customers has his own generating station; the power cost will be made up of the same items, which can be very easily demonstrated to a prospective customer."

The only exception I would make to that is the last clause—it is not always so easy to demonstrate to the possible customer that he has any fixed charges. So many of them are apt to consider that the cost of the labor, the cost of the coal that they use, and the other incidental operating expenses are the only expenses that enter into the cost, and when you call their attention to interest on investment and depreciation, and some of these other items which are absolutely a part of the cost, they are apt to get back at you with the statement that the plant has long ago paid for itself, consequently no interest charge should apply, and they maintain the plant in good operating condition, and it is, therefore, not a part of their bookkeeping to make

any charge for depreciation. I think that if the average owner and operator of a power generating plant would consider these points a little more carefully than they have done in the past, that perhaps their ideas as to the cost of generating would be materially altered.

There is another point which I had intended to speak about, but which has been covered very fully by Mr. Swann, and that is the question of the primary charge based, say, upon a kilowatt of demand. The paper states: "It is usually not possible to arrange the fixed charge that a large customer pays so that it will cover the total fixed charges of the station." I do not consider that that is altogether necessary, that it should cover, because of the fact of the diversity factor that enters into a large system supplying power to a number of different customers, whose demands on that station come at varying periods, so that there is no great likelihood of one peak being superimposed upon another, and thus making unusual demands upon the plant and requiring it to carry a very high reserve capacity.

So far as I am able, I should like to endorse absolutely the remarks of Mr. Swann with regard to uniformity of treatment of various customers. That is the only way that it is possible to sell either service or a commodity. One man's money is as good as another man's, and so long as one man makes the same use of the facilities which the central station offers him as another one, these two men should be treated exactly alike.

There is another point I should like to bring out, and that is that it seems to me there has been an unnecessary discussion of the rate per kilowatt-hour. I do not believe that that is of as much real interest to the purchaser of power as the amount of his bill. I do not believe that there is an operator who cares very much what his rate per kilowatt-hour may be, provided the total cost of power purchased from the central station is less than he can produce the same quality service for himself, and whether your rate be 15 or 20 cents per kw-hr., and you can save him money in the course of a year, he is your customer for all time and your friend as well. So that while there is a great difference of opinion as to what constitutes the proper rate, and as Mr. Lincoln has pointed out, a proper rate, an ideal rate, from the central station standpoint, is usually almost impossible of explanation to the man who is not familiar with the problems of the central station, yet I think it is possible to incorporate all or nearly all of the elements of an ideal rate in such a way as to at least appear reasonable to the man you are attempting to deal with, even though he does not understand all of it, and that lends even greater force to what Mr. Swann has said in regard to uniformity of treatment of various customers. If they feel that you are dealing fairly with them, and that each man gets the same rate as his neighbor, and they will soon find it out if he is not, the question as to whether the rate is properly constructed and whether it is readily understandable, becomes a secondary matter.

S. B. Storer: The question of rates is one I have been considerably interested in for the last ten years, and I am glad to see that so many of the expressions of sentiment here this morning indicate a tendency to one system—that of a maximum demand charge plus a kilowatt-hour charge. If there is one thing that upholds the belief that that is the only fair system, it is a continual attempt to sell power for a number of years to all classes of consumers. Furthermore, all seem to realize the growing necessity of having an absolutely uniform contract. The feature of how the maximum demand is to be measured is one that every customer tries to settle to meet his own conditions, so that his longest peak will not be subject to that measurement. In all of the contracts which I have negotiated personally, the duration of the peak has been limited to 60 seconds. That may sound pretty short, but it might better be 30 seconds than 60 seconds, and it would still be equitable alike to the consumer and the power company.

To show, as an extreme case, that that is not too short a time, I can refer to one particular factory that I have in mind, a sheet steel rolling mill located near Buffalo where power is purchased on the basis of their load factor, the demand being on a one-minute basis. While the contract itself provided that the demand might be measured either by the average load for one minute or by a block peak for one minute, as obtained by a line drawing wattmeter, the measurement at first was made by a meter of the latter type. For a considerable period of time, the load factor month by month was determined at 125 per cent, or in other words, they never had a peak that lasted over 10 to 15 seconds, it being caused by a quick shoot of the metal through the rolls. The line-drawing wattmeter would make a momentary stab and drop down again. The result was that the sustained one-minute demand was simply the friction load—coupled with a small supply of energy to the flywheel, which, of course, smooths out the peaks a trifle. As a load factor of 125 per cent is an absurdity, the only thing that could be done was to call it 100 per cent and charge it on a kilowatt-hour basis.

The fair way to get at a demand charge is to arrive at a time element so that if it is in use over a very large system, the demand will be shown in the operation or action of the governor controlling the prime mover, whether a waterwheel, steam engine, or gas engine. If it is a momentary fluctuation, the stored energy in the revolving elements operating in connection with the transmission system will take care of it. A waterpower plant having a capacity of 100,000 h.p. will take a momentary demand on a railway system of 500 or 1000 h.p. and the governor may not show it, but if that demand lasts for 30 or 60 seconds the entire system is slowed down in speed sufficiently so that the waterwheel governor opens the gate to compensate for the extra load. To my mind, therefore, any system of charging to be equitable alike to the power company and the consumer

should take that feature into consideration. A steam plant can stand a peak of much longer time with safety, due to the stored energy in the boilers, than can any water plant which usually has no overload capacity in the wheel.

The fixed charge, as a proportion of the total cost, may in general be made considerably less with a steam plant than with a water plant, on account of the lower investment, but the kilowatt-hour charge must be correspondingly higher, due to higher operating costs. Twelve dollars per kilowatt-year as a fixed charge on a steam plant is fair to customers of almost all sizes, but on a water-power system, you must take into consideration the diversity factor to a much greater extent, and a user of 5000 h.p. should pay a great deal higher rate per horse power year or kilowatt-year, on the maximum demand, than the little fellow does. To my notion, the ideal system makes use of a low service charge per kilowatt-year for little consumers, perhaps of 5, 10, 15, 20 h.p., or even up to 50 h.p., and that may be $12 per kilowatt-year on their installed capacity or their contract amount of power, as they ordinarily require it, but if you put on a 5000-h.p. customer, your diversity factor is so cut down, that, as a general proposition, the rate per kilowatt-year should be 50 per cent more than it is to the small customer. Most of the contracts which I have negotiated take that feature into consideration and have a continually increasing kilowatt or capacity charge, from the smallest to the largest. To compensate for the increasing service charge rate, and also to meet the commercial conditions arising under actual operating systems, the kilowatt-hour rate for the small consumer is made perhaps 1.5 or 3 cents, while for the very large consumer it is only 3 or 4 mills, the service charge making up about one-half or even two-thirds of the total cost of power to the consumer.

I quite agree with the last gentleman who spoke that the average consumer does not care anything about the kilowatt-hour rate, provided his monthly bill is reasonable. While it is a statement of a somewhat retrogressive character, I am going to say that I think most of the tests to determine what the average manufacturing plant or any other power consumer uses, and what the bill is going to be, is pretty much time wasted. A good power salesman, with considerable experience, having a line of consumers with whose plants he is familiar, can tell what each plant ought to operate at, and if he has the courage of his convictions and believes it, and his power company has its nerve with it, they will go in and tell that customer— "We will equip your plant, supply it with power at our standard rates and you will run the plant with this power for a year. If at the end of that time the results do not appeal to you or you are not satisfied with the bills or service, you can discontinue its use and we will take the apparatus off your hands at what it cost you." I have used that same method repeatedly when it was impossible to convince certain manufacturers that their costs for electric

power would be within a reasonable limit. They did not care about that. They knew that it cost them very much less for power than the figures we mentioned, but they were willing that we should put in an equipment on the basis which I have outlined, and we have never yet been called upon to take back the apparatus. Service is the meat of the whole power discussion, and whether it is one basis of charging, or another, does not materially affect the consumer, so long as the result is satisfactory; but it is necessary, because of public service commissions, and because of swapping of stories back and forth between consumers, to have a power contract which is absolutely uniform for all of them, and you cannot get that by giving a five-minute peak to one customer, a fifteen-minute peak to another and half-hour peaks to others.

Graham Bright: I have not very much to say in closing the discussion on this paper. Mr. Lincoln made the remark that there was not an instrument at a reasonable price, available at present for making a proper record as mentioned in the paper, but it probably will not be very long until we can get instruments of this type. It is simply a question of time, because when there is a demand for a certain instrument it will be developed, and in my opinion it will not be long until we have instruments of the proper kind, at a reasonable price, to accomplish this service.

Mr. Vigo mentioned the difficulty of moving a steam engine around, as the plant grows, after the engine becomes too small and must be replaced by a larger one. It is quite a difficult matter to take the engine out and put a larger one in its place, but when the power supply is received from a central station, and the motor which the customer has becomes too small, it is a comparatively simple matter to slip a larger motor in its place, and use the smaller motor in some other application.

The question came up yesterday in regard to using the nameplate rating as the basis for fixed charge. There is a point in connection with this scheme which makes it rather a hardship for the customer. Very frequently in opening up a mine it is desirable to put in apparatus large enough to take care of the conditions in the future, and if the name plate ratings are taken as a basis for the fixed charge, it means that the customer is burdened with a heavy fixed charge until his apparatus becomes loaded. The result is he might buy apparatus entirely too small for his future needs, which will soon become overloaded, causing general dissatisfaction.

There is one question which has not been brought up in this discussion—Mr. Eddy mentioned it in his paper yesterday—that one of the first advantages to the operator from central station power was the decreased cost. Under certain conditions this is not always the first advantage and it is not always necessary to show an operator for a mine that his costs will decrease. In fact, I believe that in many cases an operator can afford to pay at least 10 per cent more for power secured from the central

station than it would cost him to produce it himself, due to the absence of *worry* and *care* and absence of investment, so that it is not always necessary to show the customer a decreased cost.

In regard to the policy of the central station with its customer, there has been too much secretiveness in the past, and the general opinion of the customer has been that the central station is charging all the traffic will bear. It is only by an open and liberal policy toward the customer that the central station can obtain the confidence of the public, and the central station should stand ready to make concessions to a customer who is in trouble, or has a long period of shut-down.

A paper presented at the 283d Meeting of the American Institute of Electrical Engineers, New York, May 20, 1913.

Copyright 1913. By A.I.E.E.

2400-VOLT RAILWAY ELECTRIFICATION

BY H. M. HOBART

The employment of electricity as the motive power for sections of railway on which a dense service is maintained has long since been demonstrated to be desirable from many standpoints. For such undertakings it is a point of relatively minor consequence whether the railway provides its own power house or purchases its electricity from independent undertakings. In the former case the capital outlay involved in carrying through the electrification is increased, but the total of the annual capital and operating costs is rarely much affected by the choice between these two plans. It requires a careful consideration of each specific case to determine which of the two policies will lead to the most economical result. The difference will usually be so slight as to involve no wide-reaching consequences.

Nevertheless, on the broad principle that specialization and concentration are usually in the interests of true economy, the general recommendation can be made that in cases where no obvious considerable advantage accrues to the railway from owning the electricity-generating plant, and where satisfactory terms can be obtained from an independent electricity-supply company, it is on the whole desirable to purchase the electricity, leaving the railway company to concentrate the abilities of its engineers on the immediate problems of railway operation. Usually the independent electricity-supply company should be able to provide the electricity at an attractive price for the reason that the annual consumption will usually be quite an addition to its lighting and miscellaneous power load and for the further and important reason that the time-distribution of the railway load will usually be such as slightly to improve the total load factor at the generating station. These points have been emphasized

in a paper entitled *The Relation of Central Station Generation to Railway Electrification*, presented by Mr. Samuel Insull before the American Institute of Electrical Engineers on April 5, 1912.

There are, however, other classes of railway traffic where it would be a great and often a hopeless handicap to the project were the railway to provide its own power house for the supply of electricity. These classes of traffic are, nevertheless, of great importance. They consist in relatively sparse services of high-powered trains. When the load represented by such traffic can be supplied from the same generating stations which supply power for a dense urban and suburban service, its sparse character presents no special disadvantage. But for other sections where the traffic consists chiefly or exclusively of only a few (say eight or ten) high-powered trains passing daily in each direction, a power station built and operated for the exclusive purposes of this sparse traffic, could only provide the required electricity at a cost very much in excess of the price at which it could be purchased from stations already supplying a large quantity of electricity for lighting and power purposes.

It is only during the last few years that the growth of the electricity generating and supply business has increased to the enormous extent to justify the statement that it already forms a fair approach to a complete network throughout most of the moderately-settled sections of this country. It has thus come about that in estimating upon the electrification of many important sections of railway where the traffic consists of relatively few high-powered trains per day, the estimates can be based upon the purchase of electricity from some large electricity-supply station to which the additional load will be so welcome with respect to the increase which it effects in the quantity of electricity to be manufactured annually, that, notwithstanding the irregular nature of the load, the electricity can be supplied to the railway at a very moderate price. In a later section of this paper, allusion will be made to further reasons contributing to this result.

Present Position

The upshot of this altered state of affairs is that propositions which, only a few years ago, must inevitably have been dismissed as not within the economic range for electrification may now be demonstrated to be highly attractive and from all standpoints commercially reasonable. By working out in this paper a few simple comparisons, attention will be drawn to the leading facts which must be taken into consideration in such estimates. No

attempt will be made to work out *detailed* quantitative estimates: on the contrary, the only quantitative data put forward in the paper will be of a kind to indicate tendencies and to draw attention to the general order of magnitude of the corresponding costs for steam and electric operation. The investigation will be confined exclusively to traffic of the nature indicated, namely, high-powered freight and express-passenger trains, as it is for this class of traffic that it has until recently been considered that steam locomotive methods possess inherent characteristics of an economic nature which could not be rivalled by alternatives in which electric locomotives are employed.

Let us first consider a case where it would naturally be claimed that the steam locomotive would be most strongly entrenched; namely, an express passenger service. It is not asserted that the results of the estimates which will be put forward are necessarily inconsistent with the above claim, but rather it is intended to point out that, even in so extreme an instance, there are attractive possibilities in the electric-locomotive alternative.

Express Passenger Service

An express locomotive hauling a passenger train on any one of our Eastern railways will in actual service burn at least 3.5 pounds of good coal per indicated horse power hour. As a representative train we may take for example a Pacific-type locomotive weighing, complete, 185 tons[1] and hauling 10 modern Pullman coaches constructed of steel and weighing 75 tons each. There is thus an aggregate weight of $10 \times 75 = 750$ tons behind the locomotive. Of the total locomotive weight of 185 tons, the tender accounts for no less than 70 tons. Even of the remaining 115 tons only 85 tons is carried on the three driving axles, or 57,000 pounds per axle. On the basis of a coefficient of adhesion of 0.20, the locomotive can exert a tractive effort of

$$0.20 \times 85 \times 2000 = 34{,}000 \text{ lb.}$$

before slipping the wheels. For the usual requirements of an express passenger service, this limit will rarely be approached. The total train weight amounts to

$$185 + 750 = 935 \text{ tons}$$

Typical of the service of such trains is the making of non-stop runs of, say, 100 miles in two hours. This corresponds to an

1. The 2000-lb. ton (= 0.9 metric ton) is employed throughout this paper.

average speed of 50 miles per hour. In the course of this 100-mile run, *maximum* speeds of over 60 miles per hour will be attained. The average tractive effort, taking into account the variations in speed, and assuming representative track conditions as regards curves, grades, and weight and condition of rail, for a train of this composition, will be roughly 9 lb. per ton.

The total tractive resistance will be

$$9 \times 185 + 9 \times 750 = 1670^{*} + 6750 = 8420 \text{ lb.}$$

On the basis of an efficiency of 85 per cent from the cylinders to the crank-pins, the power required, averaged over the journey, will be

$$\frac{50 \times 5280 \times 8420}{60 \times 33{,}000 \times 0.85} = 1320 \text{ i.h.p.}$$

On the basis of an average consumption of 3.5 lb. of coal per i.h.p-hr., there will be burned during the journey

$$2 \times 1320 \times 3.5 = 9240 \text{ lb. of coal}$$

or 4620 lb. per hour.

This quantity is based on the use of coal of a calorific value of some 14,000 B.t.u. per pound. Since 1 h.p-hr. = 2545 B.t.u., we may express the calorific value of the coal as

$$\frac{14{,}000}{2545} = 5.50 \text{ h.p-hr. per lb.}$$

The energy in the coal burned on the journey amounts to

$$9240 \times 5.50 = 50{,}800 \text{ h.p-hr.}$$

The energy output from the cylinders is

$$2 \times 1320 = 2640 \text{ i.h.p-hr.}$$

Consequently the "journey" efficiency from the coal to the cylinders is

$$\frac{2640 \times 100}{50{,}800} = 5.20 \text{ per cent.}$$

It is highly improbable that this "journey" efficiency is ever exceeded in routine steam locomotive haulage.

* Throughout this paper the accuracy is limited to three significant figures.

In accordance with our assumption of 85 per cent for the efficiency from the cylinders to the crank-pins, we obtain for the "journey" efficiency, from the coal to the crank pins,

$$5.20 \times 0.85 = 4.41 \text{ per cent}$$

But a considerable portion of the energy delivered at the crank-pins is consumed in propelling the locomotive itself. Of the total tractive effort of 8420 lb., no less than 1670 lb. is required for the locomotive, and only 6750 lb. remains available for propelling the train behind the drawbar. Consequently the "journey" efficiency from the coal to the drawbar is only

$$\frac{6750}{8420} \times 4.41 = 3.53 \text{ per cent}$$

It must furthermore be pointed out that coal is burned wastefully in firing up before the journey and also for a considerable time after the journey.

For the case in hand a fair value to assign to the aggregate of these two components is 3000 lb.

There must consequently be debited to the 100-mile journey a gross coal consumption of

$$9240 + 3000 = 12{,}240 \text{ lb.}$$

This reduces the net efficiency from the coal to the drawbar to

$$\frac{9240}{12{,}240} \times 3.53 = 2.65 \text{ per cent}$$

Thus per drawbar h.p-hr. we require to burn

$$\frac{5.20}{2.65} \times 3.5 = 6.86 \text{ lb. of coal.}$$

Now let us consider the hypothetical case of an *electric* locomotive hauling these 10 Pullman coaches over the same distance in the same time.

In order to provide equal margins as regards starting, accelerating, ascending grades, and operation at high speeds, we must, so far as relates to the provision of the same drawbar pull, arrange for the same weight on drivers per ton total weight of train. The steam locomotive had a weight of 85 tons on drivers

and the complete train weighed 935 tons. If the electric locomotive were built with the entire weight on drivers, then if by W we designate its weight, and remembering that the weight of the 10 Pullman coaches is 750 tons, we should have the relation

$$W : 85 = (W + 750) : 935$$

$$\text{Whence } W = 75 \text{ tons}$$

While we thus see that a 75-ton electric locomotive provides the required capacity, it is necessary, in the interests of ensuring smooth running at high speeds, to provide guiding trucks at each end.[2]

Fifteen tons is an approximate figure for the weight of each of these guiding trucks. The correct method of arriving at W, the weight of the locomotive, when, as in the present instance, the speed is such as to require two 15-ton guiding trucks, is as follows:

$$(W - 30) : 85 = (W + 750) : 935$$

$$\text{Whence } W = 108 \text{ tons}$$

The weight on drivers is

$$108 - 30 = 78 \text{ tons}$$

As now modified, we may take the complete weight of the electric locomotive as 108 tons, of which 78 tons is on drivers. For the electric equivalent of our typical steam train we thus have a train with a total weight of

$$108 + 750 = 858 \text{ tons}$$

as compared with the weight of

$$185 + 750 = 935 \text{ tons}$$

for the steam train.

For the electrically propelled train the average tractive effort for the journey is

$$9 \times 108 + 9 \times 750 = 972 + 6750 = 7722 \text{ lb.}$$

2. For locomotives whose *maximum* speed is less than 45 miles per hour, no wheels in addition to the drivers need be provided. The great advantage of the electric locomotive of providing double-end operation, is, for high speeds, only secured at the cost of providing *two* bogie trucks, one at each end. One of the bogie trucks places it on a par with the steam locomotive, in respect to single-end operation; the other truck endows it with the great advantage of double-end operation.

The average power required at the rims of the drivers works out at

$$\frac{50 \times 5280 \times 7722}{60 \times 33{,}000} = 1030 \text{ h.p.}$$

The energy expended at the rims of the drivers during the 100-mile journey is

$$2 \times 1030 = 2060 \text{ h.p-hr.}$$

It will now be shown that the over-all efficiency from the coal pile in the power house, to the rims of the drivers, is, for practically any well designed and commercially sound railway scheme purchasing its electricity from large, independent electricity-supply stations, of the order of 6.0 to 6.5 per cent.

As a representative value for the annual over-all efficiency of a large modern, steam-driven electricity-supply station (*i.e.*, the efficiency from the coal pile to the outgoing cables), we may take 11 per cent.[3]

Over-all Efficiency

When designed with due consideration for the economic balance between capital and operating costs, the annual over-all efficiency of the transmission line will usually be of the order of 95 per cent. For a dense service, the annual over-all efficiency of the substations will be at least 89 per cent, and even for a sparse service it will usually be above 78 per cent. The efficiency from the substation to the trains will be of the order of at least 93 per cent for both classes of service. The annual over-all efficiency of the train equipments will be of the order of 71 per cent

3. A few years ago 9 per cent would have been considered a high figure for the over-all efficiency of large generating stations, and efficiencies of only 6 to 8 per cent were the rule. The increase over these figures constitutes, in itself, considerable reason for reconsidering railway electrification limitations. One kw-hr. = 3411 B.t.u. A generating station has an over-all efficiency of 11 per cent when, taken over an entire year, the B.t.u. in the coal consumed per kw-hr. of output from the station, average (3411/0.11 =) 31,000. On the basis of coal of a calorific value of 14,000 B.t.u. per pound, an over-all efficiency of 11 per cent is obtained when the coal consumption for the entire year is (31,000/14,000 =) 2.21 lb. per kw-hr. of output from the power house. Over-all efficiencies of from 10 to 11 per cent were obtained as early as 1905 at generating stations in Stockholm, Berlin, Vienna. (See pages 29, 34 and 47 of the author's "Heavy Electrical Engineering," Van Nostrand), and at the Interborough's 59th St. station in New York. (See page 3 of Vol. XXV, of Trans. A. I. E. E.). Annual over-all efficiencies of 11 per cent now are obtained in the more important Edison stations. At the Interborough's 59th St. station, the annual over-all efficiency is now over 12 per cent.

for a service of frequently stopping trains, and of the order of 87 per cent for a service of trains running long distances between stops. The annual over-all efficiency from coal pile to driving-wheels is thus

for dense service, $0.11 \times 0.95 \times 0.89 \times 0.93 \times 0.71 = 0.061$
" sparse " $0.11 \times 0.95 \times 0.78 \times 0.93 \times 0.87 = 0.066$

Thus for a service of trains making long runs between stops, a value of 6.5 per cent may be considered as representative of the order of magnitude of the annual over-all efficiency from the coal pile in the generating station to the rims of the driven wheels on the train.

Let us then, in the present instance, take the over-all efficiency from coal pile to drivers, as 6.5 per cent. Then the quantity of coal (of a calorific value of 14,000 B.t.u. per pound, or 5.5 h.p-hr. per pound), burned at the electricity-supply station, which should be debited to the 100-mile journey of our express passenger train amounts to

$$\frac{2060}{5.5 \times 0.065} = 5750 \text{ lb.}$$

This constitutes only

$$\frac{5750 \times 100}{12{,}240} = 47 \text{ per cent}$$

of the amount of coal which is required in the case where the same train of 10 Pullman coaches is hauled by a steam locomotive.

The quantity of coal in the two cases may be compared as follows:

122 lb. per train-mile for steam locomotive
58 " " " " electric "

Including the locomotives in the weights of the trains, these figures reduce to

$$\frac{122}{935} = 0.130 \text{ lb. per ton-mile for the steam train}$$

and

$$\frac{58}{858} = 0.068 \text{ " " " " " electric "}$$

But on the basis of coal consumption per ton-mile of *useful* load (*i.e.*, per ton-mile *behind the drawbar*) we have:

For the steam train, $\frac{122}{750} = 0.163$ lb. of coal per ton-mile

" " electric " $\frac{58}{750} = 0.077$ " " " " "

A non-stop express run has purposely been taken in making this comparison, since it represents the case where steam locomotive methods appear to best advantage in comparison with electric locomotive methods. Had occasional stops been assumed, the comparison, as far as relates to low fuel consumption, would have been still more favorable to the electric locomotive. There are the further considerations that, first, the cost of the coal delivered at the convenient site always with purpose selected for the generating station, is materially less than the cost of the same coal by the time it is loaded on the locomotive tenders; and second, a cheaper grade of coal can economically be employed in a generating station than on steam locomotives. Thus if the comparison were carried beyond the *quantity* of coal per train-mile and reduced to terms of the fuel *cost* per train-mile the result would, in most instances, be to increase the ratio of 1 (for the electric locomotive) to 2 (for the steam locomotive), to a ratio more of the order of 1 to 3.

Steam versus Electric Operation Costs

Electricity will certainly be employed to a gradually increasing extent for trains of the character we have considered, over sections of line where the requirements of other classes of traffic have been such as to justify the electrification of the line. Typical are cases where the bulk of the traffic consists in a dense service of suburban passenger trains making frequent stops and nevertheless maintaining a relatively high schedule speed. In several other instances, it has been the difficulties and dangers attending the operation of steam locomotives in long tunnels, which has occasioned the electrification of the railway. The point which it is desired to emphasize is that it has, as yet, *never been* in the first instance, a *consideration of the merits of electrical as compared with steam locomotive methods for the operation of express passenger trains*, which has led to electrification. Rather it has been in the face of a generally accepted (and heretofore entirely reasonable) opinion that for this class of service, steam locomotive haulage is economically much the more appropriate.

It is only gradually beginning to be recognized that even for a relatively sparse service of freight trains and express passenger trains, the economies in the direction of decreased fuel consumption, decreased outlay for maintenance and repairs of locomotives, elimination of firemen on locomotives, (and the substitution therefor of an assistant engineer to be available in the event of unforeseen incapacity on the part of the responsible engineer,) elimination of heavy tender, and (which will ultimately be found to be of specially great importance), increased annual mileage per locomotive, will in many instances amply justify the capital outlay involved in electrification. Caution must, however, be used, for there are at present many cases where the traffic is so sparse, the cost of electricity so considerable, and the outlay of such magnitude, (as compared to the sparse traffic), as to demonstrate steam locomotive methods to be distinctly appropriate and to constitute the economically correct system.

However, the trend of developments is strongly in the direction of extending the legitimate field for the electrification of railways. Practically all moderately settled sections of the United States are now covered with extensive electric transmission and distribution systems of great capacity. It is becoming increasingly customary to effect interconnecting arrangements between the various systems, and it appears that there will be a rapidly-increasing tendency toward providing what will, to all intents and purposes, constitute a few large networks. Steadily increasing loads and improved machinery, accompanied by scientific management, are continually leading to reductions in the prices at which electricity can be sold at a fair profit. Thus it is rapidly becoming increasingly more practicable for railways to purchase their electricity along the line of route, thereby limiting their own capital outlay to that associated with substations, feeders, contact conductors, and rolling stock. Usually the rolling stock will constitute the largest item in the capital outlay even when the service is far from dense.

Not only is there associated with the policy of purchasing the electricity the advantage of avoiding the capital outlay for electricity generating stations and for transmission lines, but there is the important consideration that the railway load is of such a character that when superposed on the present loads supplied by the undertakings, a price per kilowatt-hour can be accepted which will be lower than the cost at which the railway could make its own electricity. The railway company will usually find that

the most suitable arrangement consists in providing its own substations and purchasing from a supply undertaking the electricity in the three-phase form in which it is delivered at the substations.

2400-Volt System

To the railway the question of so designing its system as to secure the requisite conditions with a reasonable outlay for substations and for the feeders and the contact-conductor system becomes one of much importance. For a relatively sparse service, the 2400-volt system bids fair to be adopted widely. We have seen that the average power required at the drivers of an electric locomotive hauling 10 Pullman coaches at an average speed of 50 miles per hour is some 1030 h.p. At constant speed, the efficiency of the electrical equipment on the train will be of the order of 90 per cent. The average input will thus be a matter of some 1150 h.p. But during acceleration and when ascending grades, the input will rise, say, to 1600 h.p. or (1600 × 0.746 =) 1200 kw. At 2400 volts this requires collecting a current of

$$\frac{1,200,000}{2400} = 500 \text{ amperes}$$

This current can readily be collected by pantograph trolleys.[4] Moreover, currents of much greater magnitude than this may be transmitted many miles without exceeding a reasonable pressure drop and without requiring prohibitive outlay for positive and negative feeders. The more widely apart the substations are spaced, the higher (with a sparse service) will be the load factor, and the greater will be the rated capacity of each substation (and consequently the lower will be its capital cost per kilowatt of rated capacity) and, finally, the lower will be the wages outlay associated with the

4. For a given life of the contact roller, tests reveal the following relation between the speed of a pantograph trolley and the current which can be collected:

Speed in miles per hour	Current in amperes
10	1200
20	900
30	600
40	450
60	300

When estimating on two pantograph trolleys in parallel, it is well to consider their combined capacity as only 1.75 times that of a single trolley.

operation of the substations. For 2400-volt substations, the spacing will usually be from some 30 miles apart for a relatively sparse service of high-powered trains, down to some 15 miles apart with more frequent trains. With any approach to a dense service, 1500 volts or 1200 volts would amply suffice, the substation spacing ranging from 15 miles down to some five miles. From this point downward, we come within the order of things corresponding to a very dense urban and suburban traffic. In such cases, if the area is very extensive, as at Melbourne, a 1200- or 1500-volt system may appropriately be employed, but it will be more usual and satisfactory to employ some 600 to 750 volts for the exceedingly dense traffic requirements in, through and near a great city or the metropolitan district comprising two or more adjacent cities and their suburbs. It is not only possible but will often be eminently practical and desirable to combine the use of 600 or 750 volts in the near neighborhood of a great city, with the use of 1200 or 1500 volts for more remote sections where the traffic is more sparse, and the same rolling stock will be operated indifferently from either pressure.

The decision between the use of a third rail or an overhead contact-conductor is not in any sense an embarrassing one, but is readily settled in accordance with the circumstances of each case. Good use will often be made on the same system, of overhead contact-conductors on some sections and third rail on other sections, the rolling stock being readily equipped with contact appliances for both systems.

Returning to a consideration of the 2400-volt system, it may be said that pairs of 1200-volt motors in series will, so far as control methods are concerned, take the place of single motors. The most usual plan will consist in driving four axles of the locomotive from the four motors. But 1200 volts is by no means the limiting pressure for the commutator of a railway motor and it would be sound engineering to employ four 1800-volt motors connected in 3600-volt pairs on a four-axle locomotive operated from a 3600-volt contact conductor. Where the required performance of the locomotive would make it preferable to have six driven axles, the equipment could comprise six 1200-volt motors arranged in two groups, each group being made up of three motors connected in series and regarded as a single motor so far as relates to the series-parallel control features. The objections originally made that with two motors in series driving independent axles, there would be trouble if one set of wheels slipped and occasioned

most of the voltage to be concentrated on the motor coupled to these wheels, have, in practise, not been realized. In the improbable event that difficulties should arise from related reasons in future constructions, either resort could be had to employing connecting rods, or else two motors in series could drive the same axle by each having pinions engaging with the gear wheel or gear wheels on this axle. It may be as well here to point out that for the operation of trains making runs of several miles between stops, there is less justification for series-parallel control than has been the case with the frequently starting and stopping trains for which electrical operation has heretofore been regarded as especially appropriate.

Mountain-Grade Railways

A keen interest is at present being taken in the electrification of mountain-grade divisions of main-line railways in the Western states of this country. In several concrete instances, careful estimates have demonstrated that the operating economies which can be effected by superseding with electric locomotives the steam locomotives on such railways are enormous, and are indeed, of such amounts as to defray in a very few years the initial outlays for substations, for feeders and contact-conductors, and for electric locomotives.

A chief factor contributing to this result relates to the very low cost at which the large hydroelectric supply companies in the West can profitably sell electricity for operating synchronous motors in substations. A considerable proportion of the present load of these hydroelectric undertakings consists in induction motors. The large lagging component of the current consumed by induction motors involves capital and operating costs which are very much in excess of the corresponding costs of supplying equal amounts of energy at unity power factor. Synchronous motors may with advantage be so operated as to consume a current with a large leading component. It often pays an electricity-supply company to go to the expense of purchasing and installing large synchronous motors for the express and exclusive purpose of running them idle and with high excitation, simply to neutralize the lagging component of the current consumed by the induction motor load. If the electricity-supply companies can find customers who will take upon themselves the expense of purchasing such synchronous motors and who will so operate them from the electricity-supply companies' system as to neutral-

ize the undesirable lagging component, then they are spared the necessity of themselves incurring this capital outlay for improving the conditions on their system. Although the electricity-supply companies may not be able to satisfy themselves that they can equitably pay the railway companies for operating synchronous motors from their systems, nevertheless it will be seen that exceptionally low prices, satisfactory to both parties to the transaction, should readily be agreed upon. The equitable price in such a case should be arrived at on the basis of debiting the railway company with the value of the energy delivered to the substations and crediting the railway company with the value to the supply company of the leading current drawn from the system by the over-excitation of the synchronous motors in the substations.

The electricity-supply companies' traditional objection to a railway load of the sparse character associated with the operation of mountain-grade divisions, has, in the past, related to its very poor load factor. But when it is understood that these Western hydroelectric companies already have enormous loads connected to their systems, it will be seen that the fluctuations of a couple of thousand kilowatts, more or less, imposed by the intermittent operation of a few freight trains, is not a factor of consequence, especially since it does not affect the leading component of the current consumed by the synchronous motors.

Engineers have in the past usually erred in their ideas regarding the order of magnitude of a railway load. The present electricity-supply companies distributed about the country could often handle the load corresponding to relatively large railway undertakings without incurring the expense of any very considerable extensions of their generating and transmitting installations.

Let us illustrate this point by the case of the Butte, Anaconda and Pacific Railway, which is electrifying 90 miles of track with the 2400-volt system. The equipment comprises 15 freight locomotives and two passenger locomotives, each of these 17 locomotives weighing 80 tons. Although the undertaking involves transporting annually five million tons of ore over a distance of some 26 miles, the quantity of electricity which will be consumed annually at the substations will only be of the order of less than 20 million kw-hr. A single 5000-kw. turbo-generator with a total weight (including steam-turbine, generator and their common base and bearings) of only some 115 tons, often turns out this quantity of electricity in the course of a year. Only two sub-

stations (26 miles apart) are required for the undertaking, and each substation contains only two motor-generator sets, each set having a *rated* capacity of 1000-kw. and an ample *overload* capacity to carry 3000 kw. for 5 minutes at intervals. The four motor-generator sets only aggregate a total weight of some ($4 \times 45 =$) 180 tons. The only items of large consequence involved in the electrification of this undertaking are, on the one hand, the 17 locomotives, and, on the other hand, the provision of the overhead contact line, the track bonding and the positive and negative feeders.

Trailing loads of 3400 tons[5] will be hauled by two of these 80-ton locomotives (operating as a single machine) from Butte to Anaconda over a route with a maximum grade of 0.3 per cent. For such a case we no longer have the condition which, as we have seen, so greatly affects the economy of the express-passenger proposition, namely, that the weight and friction of the locomotive constitute considerable percentages of the weight and friction of the entire train. Taking the friction of the trailing load (with reasonable allowance for curves), at 4 pounds per ton, the drawbar-pull on a 0.3 per cent grade amounts to

$$(0.3 \times 20 + 4) \times 3400 = 34{,}000 \text{ lb.}$$

When returning empty, the trailing load of some 1000 tons must be drawn up maximum grades of one per cent. The tractive effort for the empty cars will be 8 lb. per ton and the drawbar pull will then be

$$28 \times 1000 = 28{,}000 \text{ lb.}$$

Obviously, even for the heavy freight service on this mountain division, the use of two of these 80-ton locomotives will give a very wide margin of excess capacity. Each 80-ton locomotive will develop continuously a tractive effort of 25,000 lb. at 15 miles per hour. For the 160-ton combination this corresponds to a continuously sustained drawbar output of

$$\frac{15 \times 5280 \times 2 \times 25{,}000}{60 \times 33{,}000} = 2000 \text{ h.p.}$$

On a level track, higher speeds will be available. At starting, the 160-ton combination will provide a tractive effort of

$$(160 \times 2000 \times 0.25 =) \, 80{,}000 \text{ lb.}$$

5. Many trains will be so much lighter as to require the use of only one 80-ton locomotive. Single locomotives will also be employed in the yards and at various points of the system as switchers and pushers.

for a 25 per cent coefficient of adhesion

$$\text{or } (160 \times 2000 \times 0.30 =)\ 96{,}000 \text{ lb.}$$

for a 30 per cent coefficient of adhesion.

This tractive effort can also be provided by a Mallet locomotive with 160 tons on drivers. The engine and tender will, however, weigh some 250 tons and the weight on each of the six driven axles amounts to

$$\frac{160 \times 2000}{6} = 53{,}500 \text{ lb.}$$

as against a weight of only

$$\frac{160 \times 2000}{8} = 40{,}000 \text{ lb.}$$

on each of the eight driven axles of the electric locomotive. Obviously on the single score of the distribution of weight, the track conditions are distinctly less severe with the electrical alternative. There is also the important advantage, in the case of the electric locomotive, that the torque is uniform and in striking contrast with the pulsating torque of the steam locomotive.

But the essential contrast as regards relative capacities is brought to light when we state that the Mallet locomotive, when burning lignite of a calorific value of some 11,000 B.t.u. per pound, can, when exerting a drawbar pull of 60,000 lb., only maintain a sustained speed of some 6.5 miles per hour. Under these conditions the locomotive will be consuming about 7500 lb. of coal per hour, and will be developing

$$\frac{6.5 \times 5280 \times 60{,}000}{60 \times 33{,}000} = 1040 \text{ drawbar h.p.}$$

If the 250-ton Mallet locomotive is hauling a 3400-ton train, then the indicated horse power will be about

$$\frac{3650 \times 1040}{3400 \times 0.75} = 1500 \text{ i.h.p.}$$

The calorific value of the lignite employed as fuel may also be expressed as

$$\frac{11{,}000}{2545} = 4.32 \text{ h.p-hr. per pound}$$

Thus the efficiency from the coal to the cylinders is

$$\frac{1500 \times 100}{7500 \times 4.32} = 4.63 \text{ per cent}$$

This efficiency estimate is on the basis of a fuel consumption of

$$\frac{7500}{1500} = 5.00 \text{ lb. of lignite per i.h.p-hr.}$$

The efficiency from the coal to the drawbar is

$$\frac{1040}{1500} \times 4.63 = 3.22 \text{ per cent}$$

The coal consumption per drawbar h.p-hr. is

$$\frac{4.63}{3.22} \times 5.00 = 7.20 \text{ lb. per drawbar h.p-hr.}$$

When, however, we take into account the coal wastefully burned during the large part of the time during which the steam locomotive is standing still, we arrive (for mountain-grade freight service), at figures of the order of from 10 to 12 or more pounds of lignite burned per drawbar h.p-hr. On the basis of 10 lb. per drawbar h.p-hr. the efficiency from the coal to the drawbar works out at

$$\frac{7.20}{10} \times 3.22 = 2.32 \text{ per cent}$$

Even when, as will usually be the case in the West, the electric proposition involves obtaining energy from hydroelectric undertakings, it is nevertheless instructive to give close attention to these efficiency and coal consumption figures, and to contrast them with the results which may be obtained with the equivalent electricity generating station in which coal fuel is employed. It has already been stated that in such a case, some 6.5 per cent of the energy in the coal burned at the generating station is delivered at the rims of the drivers. We have now seen that for the freight service in question, an electric locomotive weighing 160 tons, when compared with a steam locomotive weighing with tender some 250 tons, yields at least as great a drawbar pull at starting, since with the same weight on drivers it replaces a pulsating torque with a

constant torque. Furthermore it can develop this drawbar pull at 14 miles per hour as against less than half this speed for the steam locomotive.

The electric locomotive requires to be manned only by one engineer, although, as a precautionary measure, an assistant engineer accompanies him on the locomotive. But when, as in the instance we have considered, a Mallet is burning 7500 lb. of coal per hour, it is considered that it is beyond the capacity of a single fireman, and for *sustained* efforts of this amount, *two* firemen should be provided. In other words, in order to work up to a consumption of 7500 lb. of coal per hour (corresponding to a speed of 6.5 miles per hour with a drawbar pull of 60,000 lb., making 1500 i.h.p.) two firemen are necessary if these conditions of speed and drawbar pull are sustained for considerable periods. Thus a crew of three men are required on the steam locomotive when only 1500 i.h.p. are developed, while on the electric locomotive just one man is actually necessary (although two are provided for the reasons stated), even when the locomotive is developing over 2000 h.p.

Capital Cost and Maintenance

Finally, as regards capital outlay and maintenance. Electric locomotives with the axles driven through gears cost a matter of some $450 per ton and the outlay for repairs and maintenance runs to some 4 cents per mile per 100 tons of weight of locomotive. The outlay for repairs and maintenance of steam locomotives is about of the order of 10 cents per mile per 100 tons of weight, and since steam locomotives are inherently incapable of the mileage per annum which can be obtained from electric locomotives, then notwithstanding that steam locomotives cost considerably less than half as much *per ton of weight*,[6] the charges per locomotive-mile for repairs and maintenance, plus interest, taxes, insurance and amortization, are inherently decidedly greater for the steam locomotive than for the electric locomotive. Electric railway engineers are satisfied that these are conservative ratios. That the values which will ultimately be established will be still

6. This ratio of costs is only in small part due to any *inherently* greater cost per ton in the case of electric locomotives. It is chiefly due to the fact that whereas several thousands of *steam* locomotives are built *every year*, there are not more than a matter of 1000 *electric* locomotives *in existence*, and only 100 to 200 are built annually. The number of steam locomotives in the United States, the United Kingdom, Germany and France aggregates over 100,000.

more favorable to the electric locomotive will only slowly be demonstrated in practise, largely for the reason that conventional methods of operating railways have been so evolved as to conform with the properties and limitations of the steam locomotive. Emancipation from these limitations will not immediately be followed by a revolution in methods of operating railways. On the contrary, the electric locomotive will for some time to come be compelled to conform to the conventions of the past. Advantage will only gradually be taken of the electric locomotive's inherently greater capacity as regards speed (in the case of freight haulage) for a given drawbar pull. It will be some considerable time before methods will so be modified that, in virtue of its greater capacity for speed in freight haulage, and in virtue of freedom from the necessity of devoting a large percentage of time to overhauling it and taking it out of service for repairs*, 50 per cent or even 100 per cent more mileage per annum will be obtained from the electric locomotive than has been found expedient with its steam predecessor. Most of the present overtime expense will be eliminated with electric operation and this in itself will effect a large saving in crew expense.

The circumstances attending specific cases vary so greatly as to render it exceedingly difficult to work out quantitative comparisons. Furthermore, a reasonable consideration for commercial interests of various sorts, requires that indications of price shall be only *relatively* correct and of the right general order of magnitude. But notwithstanding the frank admission that the figures employed in the following comparison are purposely so selected that they are only quite roughly correct, and amply conservative at the present state of the art, they nevertheless, taken *relatively*, as contrasting electric with steam working, bear a very correct ratio to one another, and will be amply sufficient for the purposes of a rough comparison.

Hypothetical Example

Let us contrast the case of employing 10 electric locomotives weighing 160 tons each, and with the entire weight on drivers,

* While a comparatively short run necessitates that the steam locomotive be temporarily withdrawn from service for several hours for adjustments, cleaning and other attentions, no such limitations obtain in the case of the electric locomotive. Moreover it can be arranged that the engineer and his assistant shall relieve one another at frequent intervals, thus maintaining their strength and alertness to a degree quite impossible for the engineer and fireman constituting the crew of a steam locomotive.

with the alternative of employing 15 steam locomotives of the Mallet type, weighing, with tenders, 250 tons each, of which 160 tons is on drivers. Let the work to be performed consist in hauling freight. Let the conditions governing the capacity per steam locomotive consist in the requirement of hauling 1400-ton trains up long 1.5-per cent grades at 6.5 miles per hour, and starting 1400-ton trains on 1.5-per cent grades, and let it be proposed that the electric locomotives shall start and haul trains of the same weight over the same grades at speeds 50 per cent greater. Let the total length of single track, including terminals and sidings, be a matter of 50 miles.

Let each electric locomotive traverse 24,000 traffic miles per annum as against 16,000 traffic miles per annum for each of the steam locomotives.[7] In both cases the total traffic amounts to 240,000 locomotive miles per annum.

When hauling a 1400-ton train up a 1.5-per cent grade at 6.5 miles per hour, the output at the drawbar is

$$\frac{6.5 \times 5280 \times 38 \times 1400}{60 \times 33{,}000} = 923 \text{ h.p.}$$

The corresponding output from the cylinders of the 250-ton steam locomotive is

$$\frac{1670 \times 923}{1400 \times 0.75} = 1450 \text{ i.h.p.}$$

On the basis of employing as fuel Western lignite of a calorific value of 11,000 B.t.u. per pound, (4.32 h.p-hr. per pound), the coal consumption may be taken at 5 lb. per i.h.p-hr. while the

7. Experience has demonstrated that an electric locomotive will be available for service every day for eleven out of the twelve months of the year, the remaining month affording a liberal margin for general repairs. During the (11/12 × 365 =) 334 days of service, even a low-speed electric locomotive hauling freight over a mountain division, will readily yield 100 miles per day. This works out at an annual mileage of 33,400. It is exceedingly conservative to cut this down to 24,000 miles, or an average of (24,000/334 =) 72 miles per day, averaged over 334 days, or (24,000/365 =) 66 miles per day, averaged over 365 days.

On the other hand, to credit each steam locomotive with (16,000/365 =) 44 miles per day, when averaged over the 365 days in the year, is to take an exceedingly high figure which is seldom if ever reached by Mallets when dealing with the class of service on which the example is based.

locomotive is hauling its train under these conditions of maximum load. Thus we have a coal consumption of

$$\frac{1450 \times 5}{6.5} = 1120 \text{ lb. per train-mile}$$

Let it be premised that the average load for the entire 16,000 traffic miles traversed by the locomotive in a year, is only one-third of this maximum load. The average coal consumption with which the locomotive must be debited per train-mile, will not, however, fall to 1120/3 = 373 lb. per train-mile, for we must make allowance for the large amount of coal burned in the course of the many hours during which the locomotive is standing still, but with fires up.[8] We shall be decidedly favoring the steam locomotive in this comparison if we debit it with an average coal consumption of 560 lb. per locomotive-mile for the 16,000 miles which it travels annually. On the basis of $2.50 per ton, the fuel cost amounts to

$$\frac{560}{2000} \times 2.50 = \$0.685 \text{ per train-mile}$$

In the case of the electric locomotive we shall supply the drawbar pull at a 50 per cent higher speed. Consequently on the 1.5-per cent grades, the power at the drawbar will be

$$923 \times 1.5 = 1390 \text{ h.p.}$$

8. At page 53 of Ripley's "Railroad Rates and Regulations" (Longmans, Green and Co., 1912), the author, in discussing the cost of fuel for motive power, writes: "This item, amounting in 1905 to no less than $156,000,000 for the railroads of the United States, was the largest in the budget, constituting 11 per cent of all operating expenses. Yet brief consideration shows that even here much of this expense is constant and invariable. A locomotive will burn fully one-third as much coal merely to move its own weight as to haul a loaded train. Five to ten per cent of its total daily consumption is required merely for firing up to the steaming point. Twenty-five to 50 pounds of coal per hour go to waste in holding steam pressure while a freight train is waiting on a siding. Every stop of a train going thirty miles per hour dissipates energy enough to have carried it two miles along a level road. In brief, expert evidence shows that of this important expenditure for coal 30 to 50 per cent is entirely independent of the number of cars or the amount of freight hauled."

The output at the drivers of the electric locomotive will be

$$\frac{1560}{1400} \times 1390 = 1550 \text{ h.p.}$$

The input to the locomotive will be

$$\frac{1550 \times 0.746}{0.87} = 1330 \text{ kw.}$$

The input to the substations per train-mile will be

$$\frac{1330}{0.93 \times 0.78 \times 6.5 \times 1.5} = 188 \text{ kw-hr.}$$

But this input corresponds to the load on the ruling grade. We have already premised an average load equal to one-third of the maximum load. Consequently we have

Average input to substations $= \frac{188}{3} = 63$ kw-hr. per locomotive-mile.

On the basis of a price of one cent per kw-hr. delivered to the substations, the average cost of the electricity per locomotive-mile comes to

$$63 \times 0.01 = \$0.63$$

This is in comparison with the average cost of $0.685 for fuel per locomotive-mile corresponding to a price of $2.50 per ton for lignite.

The item of wages for the locomotive crew, will be taken at 20 cents per mile both for the steam locomotive, and for the electric locomotive.

Appropriate *relative* figures for repairs and maintenance are $(10 \times 2.5 =)$ 25 cents per mile for the steam locomotive, and $(4 \times 1.6 =)$ 6.4 cents per mile for the electric locomotive.

As to capital outlay for locomotives, $45,000 for each steam locomotive can fairly be compared with $72,000 for the electric locomotive. This is a fair *ratio* and suggests a reasonable order of magnitude. In spite of the simplicity and strength of the electric locomotive, let us credit it with only the same life, in years, as the complicated and vulnerable steam locomotive and let us take the life as 15 years. Let taxes and insurance amount to 3 per cent. Consequently as annual charges on the capital

outlay for locomotives, we may fairly take $(5 + 4.6 + 8) = 12.6$ per cent in each case. This comes to $5,670 per annum for each steam locomotive and $9,060 per annum for each electric locomotive. These figures reduce to

$$\left(\frac{567,000}{160,000}\right) = 35.4 \text{ cents}$$

per mile for the steam locomotive and

$$\left(\frac{906,000}{24,000}\right) = 37.8 \text{ cents}$$

per mile for the electric locomotive.

Thus for the five component costs which we have considered, the results are as follows:

	Per locomotive-mile Steam	Per locomotive-mile Electric
I.—Fuel	$0.685	—
II.—Electricity	—	$0.630
III.—Wages of locomotive crews	0.200	0.200
IV.—Repairs and maintenance of locomotives	0.250	0.064
V.—Interest, taxes, insurance and amortization	0.354	0.378
Totals of above 5 items	$1.489	$1.272

These five items amount, for the 240,000 locomotive miles per annum, to the following annual outlays:

Steam	240,000 × 1.489 =	$357,000
Electric	240,000 × 1.272 =	306,000
Difference in the totals of the 5 items		$51,000

To illustrate the sensitiveness of the result on the prices of coal and electricity respectively, it should be noted that with coal at $2.80 per ton and electricity at 0.80 cents per kw-hr., the difference in the totals of these 5 items for steam and electricity increases from the above result of $51,000 to $102,000.

The wages of substation attendants and linemen will only absorb a small portion—say $15,000—of the above balances, leaving the large remainder available to be applied to liquidating the capital outlay for substations and for feeders and contact conductors and for track structures and bonding.

No degree of exactness is claimed for the above cost comparison, but it *is* claimed that the results are very indicative of large

commercial advantages in the electric operation of sections of main-line railways, especially in instances where electricity can be purchased at the substations at a cost of not much over one cent per kw-hr. It is often remunerative to large hydroelectric undertakings to supply electricity to railways at prices below one cent per kw-hr. at the substations. The dependence of the soundness of the proposition on the cost of coal and the price at which electricity can be obtained, is indicated by the result to which allusion has already been made, that the saving, in the case examined, goes up from $51,000 per annum for coal at $2.50 per ton and electricity at one cent per kw-hr. to $102,000 per annum for coal at $2.80 per ton and electricity at 0.8 cent per kw-hr.

The calculations also show equally definitely that with coal at, say, $2.00 per ton and electricity at two cents per kw-hr. or thereabouts, it would be futile to consider electrification as a means of increasing the net earnings with traffic of this nature.

Consequently the merits of a proposal to electrify such a line may often be contingent upon the presence in the vicinity of a large system supplying electricity for miscellaneous power and lighting. From such a system the electricity required by the railroad could often be supplied profitably at less than one cent per kw-hr. delivered at the substations, as against a cost which might run up to two cents or more, if the railroad had to provide its own power house for supplying exclusively the small quantity of electricity at poor load factor, required for so sparse a service of trains.

Let us, however, return to the consideration of the case on the assumption that the railroad can purchase the required electricity at some such price as 0.8 cent per kw-hr. delivered at the substations.

The total quantity of electricity annually required at the substations in the above hypothetical case, is

$$240{,}000 \times 63 = 15.1 \text{ million kw-hr.}$$

The cost of substations, feeders and contact conductors, in fact, of all work, apparatus, buildings, structures and materials required for electrification, in addition to the 10 locomotives, would, for an undertaking of this magnitude, only amount to a matter of some $600,000, more or less. Of course the precise circumstances of each case would greatly affect this total.

It may have been observed that no reference has yet been made

in this paper to the weight of the electrical apparatus constituting the motive power and control equipment of the locomotives. For the examples considered, there has been no occasion to introduce this factor. The weight of the complete electrical equipment for the 2400-volt system runs only to a matter of some 55 lb. per horse power of *continuous* capacity. In fact the electrical equipment of the Butte locomotive weighs only 53,000 lb. out of a total weight of 160,000 lb. Each 80-ton locomotive has a *continuous* capacity for maintaining a drawbar pull of 25,000 lb. at 15 miles per hour. This corresponds to a *drawbar* output of 1000 h.p. or an output *at the drivers* slightly in excess of 1000 h.p. This brings the weight down to some 50 lb. per horse power of *continuous* output *at the drivers*.

The significance of the low weight of electrical equipment is that there is ample margin to obtain the horse power capacity required at high speeds without exceeding the weight on drivers necessary for obtaining the required drawbar pull.

Electrification of a 96-mile Single-Track Mountain-Grade Division of a Main-Line Railway

Let us now consider the electrification of a link in a main-line railway, which consists of a mountain-grade division 96 miles long. At certain seasons of the year there is experienced at this link a congestion of freight traffic of so severe a nature that it becomes necessary to divert to other routes of much greater length a large percentage of the available freight.[9] The division is single-tracked with 15 sidings at an average distance of six miles apart, thus dividing the 96 miles into sixteen sections of varying length but averaging six miles each. The character of the route is such that double tracking would involve enormous expense. This is often the case on mountain-grade divisions.

The trains negotiate an altitude of 3800 ft. in 48 miles and return to the original level in the remaining 48 miles. Thus the average gradient is

$$\frac{3800 \times 100}{48 \times 5280} = 1.5 \text{ per cent}$$

The ruling gradient is 2.2 per cent. There are occasional 2.5 per cent gradients but these are so short that they may be dealt

9. While the extent of the freight congestion assumed in this example is doubtless extreme, the rapidly expanding freight business of the country is leading to conditions of this order of seriousness.

with as "momentum gradients" and are not determinants in arriving at the correct powering of the trains.

It is proposed that electric locomotives shall carry over this division trains of weights ranging from 900 to 1800 tons (exclusive of the weights of the locomotives), and that while ascending, the average speed between stops shall be 12 miles per hour. Where the grade is in excess of the average value of 1.5 per cent, the speed will be less than 12 miles per hour, and for gradients of less than 1.5 per cent the speed will be in excess of 12 miles per hour. The range of variation will, however, be only of the order of from 9 to 15 miles per hour.[10] Ascending trains will be operated over the main track, and the number of stops will be reduced to a minimum. Descending trains will be operated at slightly higher speeds in order that they may be out of the way in the sidings when the ascending train arrives. Obviously on the basis of an average speed of 12 miles per hour, the 96-mile journey would require 8 hours were the ascending train to make no stops. On this *admittedly theoretical* hypothesis, and with trains in each direction simultaneously occupying alternate sections between sidings, the 96-mile division could contain simultaneously 8 trains traveling in each direction, (or a total of 16 trains), and trains could be sent into the division from each end of the division at the rate of one per hour. Thus there could be 24 trains passed over the division in each direction per day. This leads us to the (theoretically) limiting capacity of

$$48 \times 96 = 4600 \text{ train-miles per day}$$

In *practise*, however, after making reasonable allowances for unequal distances between sidings, variations in speed due to varying grades and curves, delays at the terminals of the 96-mile division, inevitable stops even of the ascending trains, and other causes for irregularity, the practical limit of the capacity of the division may be taken as of the order of

$$(0.75 \times 48) \times 96 = 36 \times 96 = 3460 \text{ train-miles per day}$$

This is on the basis that there shall be only (36/2 =) 18 trains instead of 24 in each direction per day.

Traffic of this intensity will, however, occur only during 100 days in the year. For the remaining 265 days, the freight to be transported will require only the equivalent of twenty-four 900-

10. A few passenger trains will be sent over the division every day. But to simplify the investigation, it will be assumed that these are taken into account by their equivalent in freight traffic.

ton trains per day, or twelve 900-ton trains in each direction, whereas for the 100 days of dense traffic, the 36 trains per day will each represent 1800 tons behind the drawbar.

Thus there will be transported annually over the division a total tonnage behind the drawbar, amounting to $100 \times 36 \times 1800 + 265 \times 24 \times 900$[11] $= 6{,}500{,}000 + 5{,}700{,}000 = 12{,}200{,}000$ tons, or $96 \times 12{,}200{,}000 = 1{,}170{,}000{,}000$ ton-miles.

Making reasonable allowance for the weight of the cars and for empty and lightly-loaded cars, we may take one-half of this load behind the drawbar as revenue tonnage. The paying load will thus amount to 6,100,000 tons per annum or $96 \times 6{,}100{,}000 = 585{,}000{,}000$ ton-miles.

On the basis of an average rate of 0.75 cent per ton-mile, the gross receipts amount to $585{,}000{,}000 \times 0.0075 = \$4{,}390{,}000$ per annum or $45,600 per mile of railway.[12]

The requirements of the railway as regards number and size of locomotives must be based on the seasons of dense traffic. On the ruling grade of 2.2 per cent, an 1800-ton train will require a drawbar pull of $(2.2 \times 20 + 8) \times 1800 = 94{,}000$ lb.

Drawbar Pull

Adding a further 36 per cent in order to have a safe margin for increased journal friction in cold weather, for adverse winds and for severe curves, we arrive at the value of $1.36 \times 94{,}000 = 128{,}000$ lb. as the drawbar pull which should be available when dealing with 1800-ton trains on this division. Providing a locomotive at each end of the train then each of these two locomotives will require to have sufficient reserve capacity for exerting a drawbar pull, or push, of

$$\left(\frac{128{,}000}{2}\right) = 64{,}000 \text{ lb.}$$

On the basis of a coefficient of adhesion of 0.20, each locomotive must have a weight on drivers of

$$\frac{64{,}000}{0.20 \times 2000} = 160 \text{ tons}$$

11. It is shown on the following page that the 1800-ton trains will require two locomotives and the 900-ton trains, one locomotive, consequently the annual locomotive-mileage is equal to $96 \times 100 \times 36 \times 2 + 96 \times 265 \times 24 \times 1 = 690{,}000 + 610{,}000 = 1{,}300{,}000$.

12. It is recognized that this is a high figure, but it is consistent with the hypothesis of a congested link in an extensive railway system.

Thus, so far as relates to the provision of the required tractive effort, the 160-ton Butte locomotives already described in this paper are appropriate for use on this 96-mile mountain-grade division.

The drawbar pull, when accelerating from rest (at the rate of one-tenth of a mile per hour per second) on the average gradient of 1.5 per cent, will be $(1.5 \times 20 + 10 + 10) \times 1800 = 90{,}000$ lb. or only 69 per cent of the *maximum* drawbar pull (128,000 lb.) available with a coefficient of adhesion of 0.20. When desirable, an acceleration of over a quarter of a mile per hour per second may be imparted to an 1800-ton train on the average grade.

When working the line to its utmost capacity, (*i.e.*, with a descending train in every other length between sidings and an ascending train in each intermediate length between sidings (each train having a weight, exclusive of locomotives, of 1800 tons) there would be simultaneously traversing the division 16 trains and 32 locomotives. It has already been explained that practical limitations will cut this down, either as regards the number of trains simultaneously present in the division or as regards the maintenance of the journey speed of 12 miles per hour for the 96-mile run. The actual shortage will be due partly to each of these two factors. With due allowance for additional locomotives to be available in making up trains at the terminals before entering the 96-mile division, and for spare locomotives, there should be provided a total equipment of 48 locomotives of 160 tons each.[13] This total number of locomotives is determined upon to meet the requirements of the 100 days of dense traffic. A considerable percentage of the 48 locomotives will be in excess of the requirements of the remaining 265 days of the year and will be enforcedly idle.

When handling an 1800-ton train at a speed of 12 miles per hour on a 1.5-per cent grade, we have

$$\frac{12 \times 5280 \times 90{,}000}{60 \times 33{,}000} = 2880 \text{ h.p. at the drawbar}$$

13. With the mean value of 28 locomotives (14 trains) simultaneously occupying the 96-mile section, there remain (48—28) = 20 locomotives. With four undergoing repairs, we have 16 available at termini, 8 at each end. Since these locomotives are double-ended, there will be much less time occupied than with steam locomotives in making up trains in readiness to be sent into the division.

This will be subdivided between the two 160-ton locomotives, and each will deliver 1440 h.p. at the drawbar, or

$$\frac{900 + 160}{900} \times 1440 = 1700 \text{ h.p.}$$

at the rims of the drivers.

Each locomotive has eight motors (one on each of the eight driven axles); consequently the output per motor when ascending the 1.5 per cent grade at 12 miles per hour, is 1700/8 = 213 h.p.

Since this output of 213 h.p. is the average load, the work is seen to be well within the capacity of the equipment on the Butte locomotives, for on those locomotives each motor has a continuous capacity of 250 h. p. when cooled by the forced circulation of air through it.

Weight behind Drawbar

In making up an estimate of the total annual traffic, we have arrived at the figure of 12,200,000 tons as the weight behind the drawbar passing annually over the division. Since we employ a 160-ton locomotive for every 900 tons, we shall have

$$\frac{12{,}200{,}000}{900} = 13{,}600 \text{ locomotive-journeys}$$

over the division per annum,

or $$\frac{13{,}600}{48} = 284 \text{ journeys per locomotive.}$$

Thus as an average for each one of the 48 locomotives we have a performance of 96 × 284 = 27,200 miles per annum.[14]

This is not to be taken as indicating an average mileage of 27,200/12 = 2260 miles per locomotive for *each* of the 12 months in the year. On the contrary, during the months of heavy traffic this will be greatly exceeded and during the months of light traffic a considerable proportion of the locomotive equipment will be idle and the average mileage per month per locomotive will fall greatly below 2260 miles.

14. In the footnote No. 11, we have already arrived at the figure of 1,300,000 locomotive-miles per annum. We have 1,300,000/48 = 27,200 miles per locomotive per annum, thus checking the above result in the body of the text.

At the speed of 12 miles per hour (96/12 =) 8 hours would be occupied by the journey, and each locomotive would spend 286 × 8 = 2288 hours per annum on the 96-mile division. But what with the decreased speed due to delays and the large amount of time occupied at terminals in making up trains, each locomotive would be in service with its crew for 1.5 × 2288 = 3440 hours. On the basis of eight-hour shifts and two men per crew, and an average wage of $6.00[15] per day, the wages per locomotive amount to

$$\frac{3440}{8} \times 2 \times 6.00 = \$5150 \text{ per annum}$$

$$\text{or } \frac{515{,}000}{27{,}200} = 18.9 \text{ cent per locomotive-mile}$$

Repairs and maintenance per locomotive amount to 0.04 × 1.6 × 27,200 = $1740 per annum or 4 × 1.6 = 6.4 cents per locomotive-mile.

On the rough basis of $450 per ton, we may take the price of each locomotive as 160 × 450 = $72,000.

The 48 locomotives run to a total inital outlay of 48 × 72,000 = $3,460,000.

Taking interest, taxes, insurance and amortization as aggregating 12.6 per cent on the investment for locomotives, these charges for each locomotive amount to 72,000 × 0.126 = $9060 per annum.

Cost per Locomotive

(This is on the basis of interest at 5 per cent, taxes 1.5 per cent, insurance 1.5 per cent, and a life of 15 years).

Thus we have, per electric locomotive per annum

I.—Wages of locomotive crews	$5150
II.—Repairs and maintenance	1740
III.—Interest, taxes, insurance, amortization	9060
Total of above three items	$15,950

For the 48 locomotives, this comes to a total of

48 × 15,950 = $766,000.

15. The crew of each locomotive will consist of an engineer and his mate. The latter accompanies the engineer on general principles relating to safety in the event that the engineer should be incapacitated from any cause. The engineer will receive a higher wage than this average of $6.00 for the crew, and the mate will receive less than this average. The average figure of $6.00 is high when taken in connection with the schedules at present in force, but its employment in this comparison is consistent with the purpose to favor steam-locomotive methods at all points where the reasonableness of the assumptions could be questioned.

Now let us estimate the amount of electricity consumed by the locomotives. On the ascent, the power averages 2880 h.p. at the drawbar or 3400 h.p. from the motors.

The average consumption by the locomotives works out at

$$\frac{3400 \times 0.746}{0.87} = 2920 \text{ kw.}$$

During the ascent, electricity is drawn from the line only during 48/12 =) 4 hours, notwithstanding that the ascent is only accomplished in a greater time than this.

The energy consumed during the ascent is

$$4 \times 2920 = 11{,}700 \text{ kw-hr.}$$

No return of energy to the line will be credited to the locomotives during the descent; on the contrary, an allowance of 500 kw-hr. will be made for occasional applications of power.

Energy consumed by locomotives during descent = 500 kw-hr.

Total consumption of energy by locomotives for 96-mile journey with 1800-ton train,

$$11{,}700 + 500 = 12{,}200 \text{ kw-hr.}$$

For the 900-ton trains, the consumption per journey will be

$$\frac{12{,}200}{2} = 6100 \text{ kw-hr.}$$

There are 100 × 36 = 3600 journeys per annum with 1800-ton trains and 265 × 24 = 6360 journeys per annum with 900-ton trains.

Thus the total consumption at the locomotive is

$$3600 \times 12{,}200 + 6360 \times 6100 = 44{,}000{,}000 + 39{,}000{,}000$$
$$= 83{,}000{,}000 \text{ kw-hr. per annum}$$

Increasing this by 25 per cent (*i.e.*, by 21,000,000 kw-hr.), to 104,000,000 kw-hr. per annum to allow for terminal movements and for heating of locomotives and as a margin of safety, and taking at 0.93 the annual efficiency from the substations to the trains, we obtain for the output from the substations

$$\frac{104}{0.93} = 112 \text{ million kw-hr. per annum.}$$

The annual over-all efficiency of the substations may be taken at 78 per cent. Consequently the input to the substations is

$$\frac{112}{0.78} = 144 \text{ million kw-hr. per annum.}$$

On the basis of a price as *delivered to* the substations, of 0.70 cent per kw-hr., the outlay for electricity is

$$144{,}000{,}000 \times 0.0070 = \$1{,}010{,}000 \text{ per annum.}$$

Per locomotive, this works out at

$$\frac{1{,}010{,}000}{48} = \$21{,}000$$

or

$$\frac{2{,}100{,}000}{27{,}200} = 78 \text{ cents per locomotive-mile.}$$

As to the overhead contact line, the rail bonding and the feeder copper, these will be covered liberally by an outlay of $8500 per mile. Allowing for sidings, the total outlay will be $900,000.

Finally, there will be required four substations, each for an annual output of 28,000,000 kw-hr.

On the basis of a load factor of 0.25, the *maximum* load on each substation will be

$$\frac{28{,}000{,}000}{8750 \times 0.25} = 12{,}800 \text{ kw.}$$

The *average* load per substation will be only some

$$\left(\frac{28{,}000{,}000}{8750}\right) = 3200 \text{ kw.}$$

These substations will cost, complete, with step-down transformers and motor-generators, some $160,000 per substation or $640,000 for the four substations.

Taking interest, maintenance, taxes, insurance, amortization, and labor for attendants, and linemen, as amounting to 16 per cent[16]

16. The criticism may be raised that this $246,000 should be considered in detail. To do so would only introduce uninteresting calculations. The item is relatively so small that it can consistently be dismissed without further comment than to point out that it includes an allowance of some $50,000 for wages of substation attendants, inspectors and linemen.

on this outlay of (900,000 + 640,000) = $1,540,000, we arrive at a charge of

$$(0.16 \times 1{,}540{,}000 =) \$246{,}000 \text{ per annum}$$

or

$$\frac{246{,}000}{48} = \$5130 \text{ per locomotive,}$$

or

$$\frac{513{,}000}{27{,}200} = 18.8 \text{ cents per locomotive-mile.}$$

Thus for those annual outlays which are other for electric working than they are for steam working, we have:

Loco. wages, repairs and, maintenance interest, taxes, insurance, amortization	$766,000	per annum
Electricity	1,010,000	" "
Substations and distributing system	246,000	" "
Total	$2,022,000	" "

Cost with Steam

Now how does the case stand with steam? Let us assume that a 250-ton Mallet locomotive can handle a load of 600 tons behind the drawbar over this division with the same speed when in motion, as the 160-ton electric locomotive with its 900-ton load.[17] Then when, as at times of densest traffic, it is desired to carry freight in 1800-ton trains, we shall require three 250-ton Mallets as against two 160-ton electric locomotives.

The average load at the drawbar, if equally subdivided amongst the three Mallets, is

$$\frac{2880}{3} = 960 \text{ h.p. per Mallet}$$

The drawbar pull is equal to

$$\left(\frac{960 \times 33{,}000 \times 60}{12 \times 5280}\right) = 30{,}000 \text{ lb.}$$

17. This is crediting the Mallets with a higher speed for such loads than they can maintain. Nevertheless it is desired to err on the side of favoring the steam locomotive whenever there is room for divergence of opinion.

This corresponds to an output from the cylinders of

$$\frac{(600 + 250) \times 960}{600 \times 0.75} = 1810 \text{ i.h.p.}$$

The fuel will be Western lignite of a calorific value of 11,000 B.t.u. (4.32 h.p-hr.) per pound and the consumption will be five lb. per i.h.p.

The coal consumption for a speed of 12 miles per hr. and for 600 tons behind the drawbar, thus amounts to

$$\frac{1810 \times 5}{12} = 755 \text{ lb. per locomotive-mile.}$$

But this result is arrived at on the basis that there is no wasteful consumption during stops. Unlike the electric locomotive, however, several stops will be necessary for taking on water and for coaling, and the consumption during the ascent will be increased to at least 850 lb. per locomotive-mile, or

$$48 \times 850 = 40{,}800 \text{ lb. for the ascent.}$$

The descent will occupy some 5 to 7 hours. While the power required for propulsion will be negligible for most of the descent, nevertheless, steam must be maintained in the boilers, and also, owing to the high frictional resistance of Mallet engines, power will be required for all grades materially lower than the average value of 1.5 per cent. Let us take the coal consumption as 400 lb. per hour, or (6 × 400 =) 2400 lb. for the 48-mile descent.

Thus the total coal consumption for the locomotive for the 96-mile journey, comes to

$$40{,}800 + 2400 = 43{,}200 \text{ lb.}$$

This should be increased by 20 per cent to cover the coal burned by the switching engines and also by the Mallets during terminal movements before entering and after leaving the 96-mile division, bringing the total to

$$1.20 \times 43{,}200 = 52{,}000 \text{ lb.}$$
$$= 26 \text{ tons}$$

This is an average of

$$\frac{52{,}000}{96} = 540 \text{ lb. per locomotive-mile}$$

for the 96-mile journey.

At $2.40 per ton, we have a full cost of

$$\left(\frac{540}{2000} \times 240\right) = 65 \text{ cents per locomotive-mile.}$$

Of course it is to be understood that the terminal operations are not executed by Mallets but by switching locomotives. But to simplify the calculations, the equivalent outlay is taken in terms of Mallets.

Running Time

Attention must now be drawn to the consideration that with the delays inherent to steam locomotive operation, even on the favorable assumption that the speed with three 250-ton steam locomotives and an 1800-ton train may, when running, be taken equal to the speed of two 160-ton electric locomotives and an 1800-ton train, nevertheless, the running time for the 96-mile journey, (together with the increased time consumed in making up trains at terminals with single-ended and cumbersome steam switching engines as compared with double-ended and simple electric locomotives), will certainly be at least 50 per cent greater. Thus for the 100 days of dense traffic when the division is worked to its utmost capacity, the train mileage is cut down to two-thirds of that obtained with electric operation. The limiting capacity of the line is thus reduced to

$$\frac{2}{3} \times 6{,}500{,}000 + 5{,}700{,}000 = 4{,}300{,}000 + 5{,}700{,}000 = 10{,}000{,}000 \text{ tons}$$

$$\text{or } 96 \times 10{,}000{,}000 = 960{,}000{,}000 \text{ ton-miles.}$$

Again taking one-half as revenue load and crediting it with an average rate of 0.75 cent per ton-mile we ascertain the gross receipts to be

$$480{,}000{,}000 \times 0.0075 = \$3{,}600{,}000 \text{ per annum,}$$

$$\$37{,}500 \text{ per mile of railway.}$$

We have seen that for 600 tons behind the drawbar of each locomotive, the coal consumption to be debited to the entire journey works out at 540 lb. per locomotive mile.

This is

$$\frac{540}{300} = 1.80 \text{ lb. per revenue ton-mile,}$$

or

$$\frac{1.80}{2000} \times 480{,}000{,}000 = 432{,}000 \text{ tons per annum.}$$

At $2.40 per ton, the annual outlay for fuel amounts to

$$2.40 + 432{,}000 = \$1{,}040{,}000.$$

The large amount of time required for cleaning, overhauling, repairing, adjusting and generally looking after the welfare of the steam locomotives renders it very liberal to credit each steam locomotive with an annual performance of

$$\frac{27{,}200}{1.50} = 18{,}100 \text{ miles}^{18}$$

as against each electric locomotive's 27, 200 miles per annum.

On the other hand, during the 265 days of light traffic it will be fair to estimate that one steam locomotive shall haul a 900-ton train at a slower speed, instead of hauling a 600-ton train at the higher speed at which an electric locomotive hauls a 900-ton train. Since during these 265 days the line is not worked up to its physical limitations, the disadvantage of this plan is chiefly confined to the greater outlay for wages per locomotive-mile. No greater outlay for wages on this score will, however, be debited against the steam locomotive in this comparison.

The total steam locomotive mileage during the 100 days of heavy traffic is

$$96 \times 100 \times 24 \times 3 = 690{,}000 \text{ miles.}$$

During the remaining 265 days the steam locomotive mileage amounts to

$$96 \times 265 \times 24 \times 1 = 610{,}000 \text{ miles.}$$

The total steam locomotive mileage per annum is thus

$$690{,}000 + 610{,}000 = 1{,}300{,}000$$

Consequently we must provide

$$\frac{1{,}300{,}000}{18{,}100} = 72 \text{ Mallet locomotives}$$

Each weighs 250 tons and may be taken as costing $45,000.

Thus for the outlay for locomotives we have

$$72 \times 45{,}000 = \$3{,}240{,}000.$$

18. This works out at an average of 18,100/365 = 50 miles per day averaged over the entire year. This figure is higher than that for any Mallets of which I have records, when operating on severe mountain-grade divisions.

Allowing, as with the electric locomotives, 12.6 per cent to cover interest, taxes, insurance and amortization, we arrive at an annual charge of

$$0.126 \times 45{,}000 = \$5660 \text{ per locomotive}$$

or

$$\frac{566{,}000}{18{,}100} = 31.3 \text{ cents per locomotive-mile.}$$

Each of the 72 locomotives makes

$$\frac{1{,}300{,}000}{96 \times 72} = 188 \text{ journeys per annum.}$$

Were only (96/12 =) 8.0 hours occupied by the 96-mile journey, then each locomotive would spend

$$188 \times 8 = 1504 \text{ hours per annum}$$

on the 96-mile division. But there must be taken into account the decreased speed due to delays during the journey and also the great amount of time consumed in making up trains at terminals. This handicaps operations with single-ended steam locomotives much more than with readily and promptly operated double-ended electric locomotives. It will be reasonable to assign to each steam locomotive an annual period of

$$2 \times 1504 = 3008 \text{ hours}$$

of service with its crew. The crew of the steam locomotive will consist of an engineer and a fireman working on eight-hour shifts. On the basis of an average wage of $4.50 per day, (the engineer receiving *more*, and the fireman *less* than this average), the outlay for wages for each steam locomotive, amounts to

$$\frac{3008}{8} \times 2 \times 4.50 = \$3380 \text{ per annum,}$$

or

$$\frac{338{,}000}{18{,}100} = 18.7 \text{ cents per locomotive-mile}$$

Cost with Mallets

It will be noted that in estimating the wages for each Mallet, it is assumed that only one fireman will be required. However, we have already seen that 40,800 lb. of coal will be burned during the 48-mile ascent. If this ascent is accomplished in 5

hours, the coal consumption amounts to 8200 lb. per hour; if in 6 hours, 6800 lb. per hour. It is often maintained that *two* firemen should be provided when it is required to fire such great hourly quantities of coal.

Repairs and maintenance per locomotive amount to

$$0.10 \times 2.5 \times 18{,}100 = \$4250 \text{ per annum}$$

(This is on the basis of $10 \times 2.5 = 25$ cents per locomotive-mile)

Thus per steam locomotive per annum we have

I.	Wage of locomotive crews	$3380	per annum
II.	Repairs and maintenance	4250	" "
III.	Interest, taxes, insurance, amortization	5660	" "
	Total of above three items	$13,290	" "

For the 72 locomotives we have

$$72 \times 13{,}290 = \$956{,}000.$$

Bringing together the annual outlays which should be compared with those previously set forth as relating to equivalent operation by electricity, we have

Locomotive wages, repairs, maintenance, interest, taxes, insurance, and amortization	$956,000	per annum
Coal	1,040,000	" "
	$1,996,000*	" "

But, whereas the electrical outlay of $2,022,000 per annum was associated with a revenue of $4,390,000 per annum, leaving a difference of $2,368,000 per annum to be applied to the outlays common to both systems and to reserves, the corresponding steam outlay of $1,996,000 per annum is associated with the reduced revenue of only $3,600,000 per annum, leaving a difference of only $1,604,000 to be applied to residual outlays and to reserves.

$$\frac{1{,}604{,}000}{2{,}368{,}000} = 0.68$$

Thus the residual amount with steam is only 68 per cent of that with electricity.

*No charge is made to cover outlays for round-houses, water tanks, structures for coal stores and other works incident to steam locomotive operation and not required when electric locomotives are adopted.

It will be agreed that the correct basis for estimating the commercial results to accrue from electrical operation is to compare all those items which are affected by the use of electricity instead of steam. This is, however, inconsistent with the retention of the forms which have become customary in analyzing the results of steam operation. Consequently, as of probable interest, the locomotive operating expenses per locomotive-mile are tabulated below.

	Operating expense in cents per locomotive-mile	
	Steam locomotive	Elec. locomotive
Fuel	65.0	0
Electricity	0	78.0
Repairs	20.0	5.6
Wages	18.7	18.9
Engine house expenses	3.5	0
Lubricants	0.9	0.5
Stores	0.6	0.3
	108.7	103.3

These figures only apply to the particular 96-mile mountain division which has constituted the subject of our analysis and to the particular prices employed for coal ($2.40 per ton) and electricity (0.70 cent per kw-hr.)

For the electric proposition there is an average load of 900 tons behind the drawbar for every electric locomotive. But from the data previously given we see that the average load behind the drawbar for the steam locomotive is only

$$\frac{960,000,000}{1,300,000} = 740 \text{ tons.}$$

Consequently to reduce the locomotive operating costs to comparable terms let us take as a standard of reference 100 tons behind the drawbar. We then have steam locomotive operating costs per mile

$$= \left(\frac{108.7}{7.40}\right) = 14.7 \text{ cents per 100 tons behind drawbar.}$$

Electric locomotive operating costs

$$= \left(\frac{103.3}{900}\right) = 11.6 \text{ cents per 100 tons behind drawbar.}$$

Let us look at the costs per locomotive-mile, per total train-mile and per 100-ton-miles behind the drawbar for the 1800-ton

train which we have more particularly investigated. This required three 250-ton Mallets or two 160-ton electric locomotives, bringing up the total train weights in the two cases to (3 × 250 + 1800 =) 2550 tons and (2 × 160 + 1800 =) 2120 tons respectively.

The results are set forth in the following table:

	Operating expense in cents per mile					
	Per steam locomotive	Per elec. locomotive	Per steam train (3 locomotives)	Per elec. train (2 locomotives)	Steam operation: Per 100 tons behind drawbar	Electric operation: Per 100 tons behind drawbar
Fuel or electricity	65.0	78.0	195.0	156.0	10.8	8.7
Repairs	20.0	5.6	60.0	11.2	3.3	0.6
Wages	18.7	18.9	56.1	37.8	3.1	2.1
Engine house expenses	3.5	0	10.5	0	0.6	0
Lubricants	0.9	0.5	2.7	1.0	0.2	0.1
Stores	0.6	0.3	1.8	0.6	0.1	0.1
Totals	108.7 per loco. mile	103.3 per loco. mile	326.1 per train mile	206.6 per train mile	18.1 per 100 ton-miles behind the drawbar	11.6 per 100 ton-miles behind the drawbar

A paper presented at the 283d Meeting of the American Institute of Electrical Engineers, New York, May 20, 1913.

Copyright 1913. By A.I.E.E.

TRUNK LINE ELECTRIFICATION

BY CHARLES P. KAHLER

The object of this paper is to show the effect of the substitution of electric motive power for steam, upon the operation of a railroad, and the comparative cost of operating a railroad by steam and electric power; also to outline general railroad conditions and show whether the return on the large investment necessary for the electrification of a steam railroad (by reason of the lower electric operating expenses and increased passenger earnings) will be likely to warrant operation by electric power.

General

The great objection to operating many of the large steam railroads by electric power is the extremely heavy investment necessary for the electric apparatus and equipment. The ability of the steam locomotive to handle railroad traffic in a very reliable, and, I may also say, expeditious manner, is very well known, but up to date, railroad managers either have not been convinced that electric motive power is as reliable as steam power or else they do not believe that the improvement in the railroad service or the saving in operating expenses resulting from electric operation will be great enough to warrant the heavy expenditures necessary. On most railroads, bonds would have to be issued to cover the cost of electrification, and the return on the investment, by reason of the lower electric operating cost, would have to be great enough to pay the interest and sinking fund on the bonds, and leave a reasonable profit besides.

Reasons for Past Electrification Work

Very little of the past work of steam railroad electrification was done on account of the financial return expected on the money

so expended. It was the ability of the electric locomotive to accomplish or do some special work not possible with the steam locomotive that caused most of the past work to be done. The first heavy electric railroad work in this country was on the B. & O. R.R., where the electric locomotives were substituted for steam locomotives to do away with the smoke troubles in the long Belt tunnel extending under the heart of Baltimore. The smoke trouble with steam locomotives has, in fact, been one of the most important reasons for the past progress in heavy electric railroad work. Steam locomotives, with their smoke and gases, could hardly do the work of the Pennsylvania electric locomotives operating through the tunnels into New York. The smoke nuisance is also the principal reason that the electrification of the Chicago terminals is being considered at present.

Results of Past Heavy Electrification Work

Irrespective of what caused the past heavy electric railroad work, the actual operation of large electric locomotives showed that they could in some ways handle railroad traffic more advantageously than steam locomotives. Also, it was found that electric locomotives were as reliable in operation as steam locomotives. In fact, the published records of the steam and electric locomotives of the New York Central Railroad, the New York, New Haven & Hartford Railroad, and the Pennsylvania Railroad, indicate that electric locomotives are probably even more reliable in operation than steam locomotives. The published records of the above roads also indicate that the quantity of fuel required to generate power in a steam-electric plant for railroad operation is much less than the fuel required by steam locomotives in the same service. Also, the locomotive repair expense was found to be much less on electric locomotives than on steam locomotives.

Further, as the electric locomotives do not have to bother with taking fuel and water, nor have a boiler or fire-box to be cleaned out, they are nearly always ready for service, and also take less time to handle trains than steam locomotives, especially on long runs. The perfection of the multiple unit control made the number of driving units which could be controlled by one man practically unlimited and, consequently, it was possible to make the size of electric locomotives much greater than steam locomotives with the boiler limitations.

The large saving in operation and other advantages which it

was evident would result from electric railroad operation, caused the manufacturers and builders of steam locomotives to make many marked improvements in the steam locomotive. The Mallet and Mikado types of locomotive, with all the refinements for economic operation, resulted partly from the competition between the steam and the electric locomotive. However, the limitations imposed by the boiler of a steam locomotive are still a big disadvantage, as any increase in tractive power of a steam locomotive can only be had by lowering the speed.

Another important point in connection with electric operation was brought out by the great success of the interurban electric railways. The frequent passenger train service, and other advantages possible on the electric railways, caused a large increase in the local passenger traffic. The passenger earnings on these interurban electric railways soon after beginning operation became much greater than had been obtained from the same territories by steam-operated railroads.

The gasoline motor car and the gas-electric motor car would probably not have been developed were it not for the trolley lines taking local passenger business away from the steam railroads. These have been successful as far as operation goes, but although some of the published costs of operation are lower than steam train operation, I know of several cases where the operating and maintenance costs of the gasoline motor cars differ very little from those of the three-car steam trains. The gasoline cars are not as reliable as a steam locomotive, and I doubt if the gas-electric cars are much better, although they are probably better fitted to handle traffic where frequent stops are necessary than the gasoline cars.

Effect of the Physical Characteristics of a Railroad on the Operating Expenses

The grades, curvature and other physical characteristics of a railroad have a very important influence upon its operating expenses and are usually very carefully studied by railroad men with a view of cutting down operating expenses. The reduction in the number of freight trains by cutting down the ruling grade is one way of reducing operating expenses. The elimination of helper engine districts, shortening of distances, taking out curvature, and lessening the rise and fall of grades, are other ways in which a great deal of money is now being expended on steam railroads to lower the operating costs.

Ruling Grade. The ruling grades are those which limit the weight of the freight trains. They are not always the maximum grades, because the maximum grades are often momentum grades. On many steam railroads where the average grade is low, the heavy ruling grades which determine the weight and thereby the number of freight trains, are comparatively short. If these roads were electrically operated, the weight of the freight trains could in most cases be made much heavier than possible by steam operation, on account of the characteristic of the electric locomotive to operate overload without dangerous overheating, long enough to get over the short heavy-grade sections, and on this account the ruling grade of an electrically operated railroad will seldom be as great as the ruling grade of a steam-operated railroad. This will be explained more in detail below.

Helper Districts. Sometimes in constructing a railroad on a certain ruling grade, there are some short sections where it is either impossible to build to the established ruling grade or else the construction expense would be prohibitive. In such cases, helper districts are established which require from one to four engines, in addition to the regular road engine, to haul freight trains with the maximum or ruling grade tonnage over them. For instance, if the ruling grade of an engine district is 0.5 per cent and there is a 1.7 per cent helper grade, while one engine could haul a freight train loaded for a 0.5 per cent grade over the engine district, two additional locomotives of the same class as the road locomotive would be required to assist the train over the 1.7 per cent helper district. Only one engine crew would be required where more than one electric helper locomotive is used, as two or more electric locomotives can be coupled together and operated as a single unit by one man, while with steam locomotives as many engine crews will be needed as there are steam locomotives used.

Influence of the Locomotive on the Operating Expenses of a Railroad

The locomotive is directly responsible for from 30 per cent to 40 per cent of the operating expenses of a steam railroad, the principal items being the fuel cost, locomotive repair cost, the engine house expenses, and the wages of the engine crew. In addition, the locomotive is indirectly responsible for a good deal of expense, as its tractive power determines the number of freight trains, and upon its reliability depends the expense due to delays from locomotive failures.

The horse power and tractive effort curves shown in Fig. 1, for a consolidated steam freight locomotive and an electric locomotive for freight service, illustrate the comparative characteristics of the two kinds of locomotives. At a speed of 16.5 miles per hour, which is only a little greater than the usual average

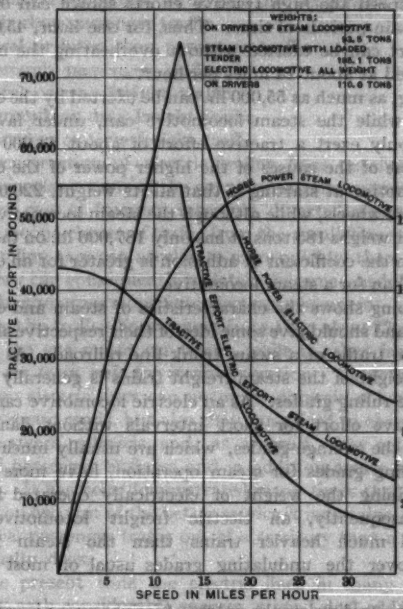


FIG. 1—CURVES SHOWING COMPARATIVE CHARACTERISTICS OF ELECTRIC LOCOMOTIVE AND CONSOLIDATED STEAM LOCOMOTIVE FOR FREIGHT SERVICE.

speed of freight trains, the tractive power of both locomotives is equal. Above this speed the steam locomotive can exert a higher tractive effort than the electric locomotive, while below this speed the electric locomotive has the higher tractive effort.

The steam locomotive can exert the tractive effort shown by the curve at the higher speeds only for short intervals, on account

of the inability of the boiler to supply continuously the necessary steam. On the other hand, the electric locomotive can not continuously exert the high tractive effort shown by the curve at low speeds, without overheating. The maximum tractive effort which can be continuously exerted by the electric locomotive with safety is 34,600 lb. at a speed of 16 miles per hour. Below this speed the high tractive efforts shown can only be used for certain periods of time. Thus, for one hour, 45,000 lb. tractive effort can be exerted without overheating the motors, with the speed at about 14 miles per hour.

At starting, as much as 55,000 lb. can be exerted by the electric locomotive, while the steam locomotive can, under favorable conditions, only exert a tractive effort of about 43,000 lb. at starting. One of the causes of the higher power of the electric freight locomotive at starting is that all its weight, 220,000 lb., is on the drive wheels, while although the steam locomotive with loaded tender weighs 185 tons, it has only 187,000 lb. on the drive wheels. Also the coefficient of adhesion is greater for an electric locomotive than for a steam locomotive.

The foregoing shows the characteristics of steam and electric locomotives and should give some idea of their respective abilities to handle the traffic of a steam trunk line railroad. As stated before, the weight of the steam freight trains is generally determined by the ruling grades. As an electric locomotive can exert a high tractive effort for short intervals without dangerous overheating, the average grades, which are usually much lower than the ruling grades for steam operation, have more to do with determining the weight of electrically operated freight trains. Consequently, an electric freight locomotive can usually haul much heavier trains than the steam freight locomotive over the undulating grades usual on most steam railroads.

On some engine districts the weight of freight trains is governed by the starting grades. Here also the electric freight locomotive has the advantage, as all or nearly all the weight is on the drive wheels and the starting capacity of any locomotive is usually proportional to the weight on the drivers.

For passenger service, the higher tractive effort at starting gives the electric locomotive a great advantage, as a higher rate of acceleration can be obtained. Also for local passenger service the higher starting power makes it possible to maintain by electric operation a much higher schedule speed with frequent stops to

collect the passengers than could be done with the steam locomotive.

Competition for Different Classes of Railroad Service

The railroad traffic may be divided into six general classes:

1. Suburban passenger traffic.
2. Local or interurban passenger traffic.
3. Through passenger traffic.
4. Local or way freight traffic.
5. Through or drag freight traffic.
6. Manifest or time freight traffic.

The construction of electric trolley lines parallel to steam railroads in many parts of the country, and the operation of electric motor cars at frequent intervals, diverted nearly all of the first and second classes of traffic from the paralleling steam roads. As the trolley cars can accelerate more quickly than the steam trains, they can consequently maintain the same schedule speed and still make numerous stops for collecting passengers. The cost of operating the trolley lines ranges from 12 *to about* 22 *cents per car mile* for the one motor car trains, while it takes from 50 *cents to* $1.40 *per train mile* for steam operation. Consequently, the interurban electric lines can not only maintain a better service than the steam roads, but also they can afford to charge less fare than the steam railroads, and, as a result, they get nearly all the local passenger business and in addition create a new class of traffic. It has been demonstrated many times that an electric line will, on account of the better service it maintains, get a much larger local passenger traffic out of a territory than a steam railroad usually does.

At the present time the electric lines in many places are handling, with considerable success, a good deal of local freight business. The electric lines have not as yet materially affected that part of the revenue of steam roads which is obtained from the through passenger and freight traffic.

The experience with the electric locomotive has demonstrated its reliability. The operating cost data available from electrified steam railroads have made it evident that many steam railroads could now be operated more economically by electric power. However, the comparative economics of steam and electric railroad operation would, of course, have to be studied for each case, and to bring out the relative advantages and disadvantages of steam and electric operation of trunk line railroads a concrete example will now be discussed.

Description of Railroad Considered

Let us consider a single-track railroad constructed through a semi-arid region, similar to many parts of the West, which contains numerous irrigated and dry farm districts. The length of the railroad will be taken as 467 miles, and be divided into three engine districts, respectively 167, 160 and 140 miles long,

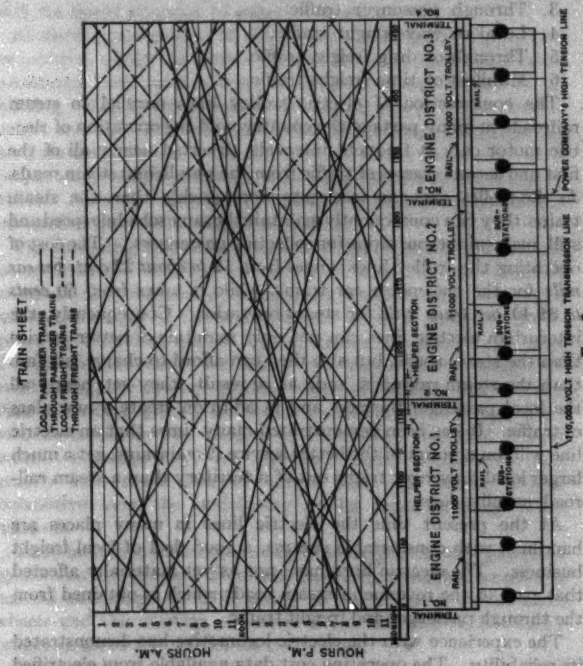


Fig 2

from the west towards the east, and will be referred to as engine district No. 1, No. 2 and No. 3, in the order named. The curvature averages about 12 degrees of central angle per mile and the ascents and descents of the grade average 18 feet per mile. The engine terminals will be referred to as terminal No. 1, terminal No. 2, terminal No. 3 and terminal No. 4, from west

towards the east. It will be assumed that there will be a helper district 9 miles in length for west-bound trains on engine district No. 1 and also one of the same length on engine district No. 2 for east-bound trains, the foot of these helper grades to be located 11 miles west of and 7 miles east of terminal No. 2 and the helper locomotives of both districts to be hostled and taken care of at terminal No. 2. The limiting grades of the three engine districts are shown in Table II. Also Table I and Fig. 2 will show the relative location of the engine districts and helper sections, together with other data of this railroad.

TABLE I

	Engine districts			Total
	No. 1	No. 2	No. 3	
Miles of main track	167.5	160	140.5	468
Miles of side track	54.5	51	50.5	156
Total main and side track	222	211	191	624
Miles curved track	35	33	32	100
Degrees of central angle per mile	12°	12°	12°	12°
Maximum curvature	6°	4°	4°	6°
Ascents and descents of grade per mile	14 ft.	22 ft.	18 ft.	18 ft.
Average grade	0.14%	0.21%	0.17%	0.17%
Weight of rail per yard	90 lbs.	90 lbs.	90 lbs.	90 lbs.

Steam Equipment. The through passenger trains to be handled by Pacific type locomotives of 192 tons weight with loaded tender, to handle from 5 to 14 coaches per train. The local passenger trains to consist of a 110-ton locomotive (with loaded tender) with a baggage car, smoking car and day coach, all cars being of 45 tons weight.

The freight trains to be handled by consolidated locomotives of total weight with coal and water of 185 tons and with 187,000 lb. on the drive wheels. The local freight trains to be handled by 130-ton locomotives.

Electric Operation. For comparison of steam and electric operation, the above line will be considered as equipped with an 11,000-volt, single-phase, 15-cycle trolley, with 110,000-volt, 15-cycle high-tension line to supply power to 14 substations. The power to be received into the high-tension system at terminal No. 3.

The local passenger trains to consist of two electric motor cars and one trailer. The through passenger trains to be hauled

by 100-ton electric locomotives. The local freight trains to be hauled by an 85-ton locomotive, which class of locomotive will also be used in switching service. The through freight trains (both expedite and drag) to be hauled by 110-ton locomotives.

Passenger Traffic. The passenger traffic to consist of six through trains per day (three each way) over the whole road. On engine district No. 1 there will be four local passenger trains per day (two each way), while on engine districts Nos. 2 and 3 there will only be two local passenger trains per day.

Freight Traffic. The annual freight traffic over each engine district will be assumed as follows:

Engine districts	Tonnage of cars and contents		
	No. 1	No. 2	No. 3
West bound:			
Expedite freight	800,000	700,000	800,000
Drag freight	1,700,000	1,700,000	1,600,000
Local freight	200,000	——	160,000
East bound:			
Expedite freight	600,000	600,000	600,000
Drag freight	1,300,000	1,300,000	1,200,000
Local freight	100,000	——	100,000

Number of Freight Trains

To determine the number of freight trains necessary to handle the above traffic, the maximum tonnage which the locomotives can haul over each engine district will have to be determined. For steam operation, this can be closely computed if the ruling and starting grades are known. Also a close approximation of the maximum tonnage by electric operation can be made if the average grades and their length are known, together with the maximum grades at starting.

However, the most accurate way of determining the maximum tonnage which can be hauled by a locomotive is to draw the velocity diagram for the limiting grade sections of the engine districts. Fig. 3 shows the profile and velocity diagrams for both steam and electric freight trains over the limiting grade sections of engine district No. 1. This will also give an idea of the variety of conditions for which a locomotive of a trunk line railroad is used.

The limiting points are determined by the starting grades, the helper grades and the ruling grades. In computing the hauling

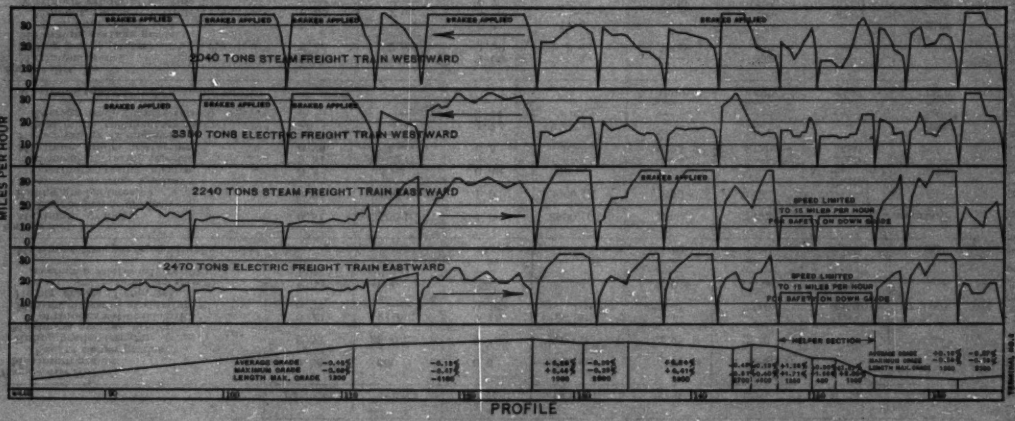


FIG 3 —PROFILE AND VELOCITY DIAGRAM OF FREIGHT TRAINS. (PART OF FIRST ENGINE DISTRICT.)

TABLE II

	Limiting grades				Tonnage per train, including locomotive			
	West		East		Steam oper.		Electric oper.	
	Per cent	Length	Per cent	Length	West	East	West	East
Engine dist No. 1:								
Maximum grades (Exc. of helper grades)	0.56	600 ft.	0.6	1300 ft.	(Momentum Grades)			
Ruling grades (steam)	0.52	3800 ft.	0.55	2300 ft.	2350	2240	—	—
Maximum average grades.								
Continuous rating (electric)	0.22	21 mi.	0.45	28 mi.	—	—	3680	2470
Maximum grades at starting	0.32	—	0.46	—	2650	2240	3350	2780
Helper grades (3 engines):								
Maximum (momentary rating)	2.00	1900 ft.	—	—	2040*	—	3450*	—
Average grade (hourly rating)	1.3	8 mi.	—	—	—	—	4140*	—
Maximum tons per train actually hauled					2040	2240	3350	2470
Engine dist. No. 2:								
Maximum grades (Exc. of helper grades).	0.81	3100 ft.	1.00	3900 ft.	1690	1432	(Partly Momentum)	
Ruling grades (steam)	0.81	3100 ft.	1.0	3900 ft.	1690	1432	—	—
Maximum average grades:								
Continuous rating (electric)	0.3	8 mi.	0.48	28 mi.	—	—	(Partly Momentum)	2370
Momentary rating (electric)	0.81	3100 ft.	—	—	—	—	2500	—
Maximum grades at starting	0.20	—	0.5	—	2725	2150	3480	2750
Helper grades (2 engines):								
Maximum (momentary rating)	—	—	1.72	2300 ft.	—	1645*	—	2680*
Average grade (hourly rating)	—	—	1.11	9 mi.	—	—	—	3200*
Maximum tons per train actually hauled					1690	1432	2500	2370
Engine dist. No. 3:								
Maximum grades	0.88	1150 ft.	1.00	2.5 mi.	—	1432	—	—
Ruling grades (steam)	0.35	2 mi.	1.00	2.5 mi.	3000	1432	—	—
Maximum average grades:								
Continuous rating (electric)	—	—	0.55	17 mi.	—	—	—	2160
Moment. rating (electric)	0.35	2 mi.	—	—	—	—	4583	—
Maximum grades at starting	—	—	0.7	—	4300	1795	5500	2290
Maximum tons per train actually hauled					3000	1432	4583	2160

*Without weight of helper locomotives

capacity for steam locomotives, it is usual to make 10 miles per hour the minimum speed in order to allow for weather conditions, the personal equation of the engineer, and other variable conditions.

In Fig. 3 it will be noted that west, bound steam freigh ttrains of 2040 tons get down to 10 miles per hour at about mile post 152, on the helper section, and hence the helper section limits the weights of steam freight trains. The starting capacity of the steam locomotive is also nearly reached with the same tonnage. For west-bound electric trains, the starting grades limit the weight to 3350 tons.

The weight of east-bound steam freight trains is limited to 2240 tons by the ruling grade, 0.55 per cent. The starting grades also will not permit a heavier steam train. The weight of the east-bound electric freight trains (2470 tons) is limited by the long 21-mile grade from mile post 82 to mile post 111, which averages 0.45 per cent, the maximum grade in this distance being 0.6 per cent. It is on these long grades, where the electric locomotive operates on its continuous rating, that the steam locomotive compares most favorably with the electric locomotive. But even here the steam locomotive's hauling capacity is determined by the ruling grade, 0.55 per cent, which is very short, while the hauling capacity of the electric locomotive is determined by the average grade, 0.45 per cent.

In like manner, the weight of the freight trains was computed for engine districts Nos. 2 and 3. The maximum grade in most cases equals the ruling grade for steam operation. The maximum average grades, which govern the weight of the electric trains, are much lighter than the maximum grades; also the average grades are not of any great length and, consequently, the electric locomotive can exert considerably greater tractive effort than its continuous capacity. As a result, the electric locomotive can haul from 50 per cent to 60 per cent greater tonnage than the steam locomotive over these engine districts.

Table II shows the limiting grades of all engine districts, together with the maximum tonnage which can be handled by the 185-ton steam consolidated freight locomotive and the 110-ton electric freight locomotive, whose characteristics are shown in Fig. 1.

Table No. III gives the maximum trailing tonnage which the steam and electric freight locomotives can haul over the different engine districts:

TABLE III

TRAILING LOAD OF DRAG FREIGHT TRAINS IN TONS

	Steam locomotive		Electric locomotive	
	West	East	West	East
Engine district No. 1	1855	2055	3240	2360
Engine district No. 2	1505	1247	2480	2260
Engine district No. 3	2815	1247	4472	2050

The above trailing weights were obtained by subtracting the weights of the steam (185-ton) and electric (110-ton) locomotives from the total train weights given in Table II. The minimum speed of the electric freight trains is considerably greater than for steam freight trains, as it ranges from 14 to 16 miles per hour, which is high enough for expedite trains. The maximum steam train weights for expedite freight trains would have to be lighter than those given in Table III, as greater speed is required. Table IV gives the weights of the expedite trains:

TABLE IV

TRAILING LOAD OF EXPEDITE FREIGHT TRAINS IN TONS

	Steam locomotive		Electric locomotive	
	West	East	West	East
Engine district No. 1	1529	1697	3240	2360
Engine district No. 2	1235	1018	2480	2260
Engine district No. 3	2335	1018	4472	2050

In actual practise, the average weight of the trains would not be as great as given in Tables III and IV, since during slack times there are not always enough cars to load the engines to their maximum and, consequently, a number of short weight trains have to be operated. For the railroad considered, it will be assumed that the weight of the expedite and drag trains averages about 80 per cent of the maximum allowable weight or tonnage rating given in Tables III and IV. The number of local freight trains is generally governed by local conditions.

Table V shows the number of freight trains per year necessary to handle the freight traffic given above.

TABLE V

NUMBER OF FREIGHT TRAINS PER YEAR

	Steam locomotive			Electric locomotive		
	West	East	*Total	West	East	*Total
Engine dist. No 1:						
Expedite trains	656	442	1312	309	318	636
Drag trains	1149	793	2298	656	688	1376
Local trains	400	400	800	400	400	800
Totals			4410			2812
Engine dist. No. 2:						
Expedite trains	809	741	1618	404	335	808
Drag trains	1417	1300	2834	859	727	1718
Totals			4452			2526
Engine dist. No. 3:						
Expedite trains	428	741	1482	225	372	744
Drag trains	711	1200	2400	450	747	1494
Local trains	320	320	640	320	320	640
Totals			4522			2878

*As it is necessary to operate the same number of trains in both directions on account of train crews and equipment, the totals, of course, are twice the greatest number of trains required in one direction.

On all railroads the traffic at some seasons of the year is greater than at others. However, it is seldom that the passenger and freight busy seasons happen at the same time. The freight tonnage is generally greatest in agricultural districts after the crops are harvested, which is generally in the fall. The time of the greatest passenger traffic will depend on local conditions but, as stated above, seldom happens at the same time as the heavy freight movements. The writer has been often surprised at how uniform the train mileage and ton mileage per mile of line is during the year. For the railroad considered, the maximum and average number of trains per day is taken as follows:

TABLE VI

NUMBER OF TRAINS PER DAY—(BOTH WAYS)

	Eng. dist. No. 1		Eng. dist. No. 2		Eng. dist. No. 3	
	Average day	Maximum day	Average day	Maximum day	Average day	Maximum day
Steam trains:						
Passenger	10.0	10.0	8.0	8.0	8.0	8.0
Freight	12.1	16.0	12.2	17.0	12.4	18.0
Total	22.1	26.0	20.2	25.0	20.4	26.0
Electric trains:						
Passenger	10.0	10.0	8.0	8.0	8.0	8.0
Freight	7.7	11.0	6.9	10.0	7.9	12.0
Total	17.7	21.0	14.9	18.0	15.9	20.0

Table VII shows the train mileage, ton mileage, and locomotive mileage necessary to handle the assumed traffic over the railroad considered. The locomotive mileage includes the mileage to and from trains and the switching locomotive mileage.

TABLE VII

	Steam Operation	Electric Operation
Train miles:		
Local passenger trains	462,820	000
" motor trains	000	462,820
Through passenger trains	1,022,730	1,022,730
Total passenger	1,485,550	1,485,550
Local freight trains	233,200	233,200
Through "	1,858,670	953,344
Work trains	81,120	81,120
Total freight trains	2,172,990	1,267,664
Total all trains	3,658,540	2,753,214
Locomotive and motor car mileage:		
Motor car mileage	000	971,922
Passenger locomotives	1,559,828	1,073,867
Local freight locomotives	240,196	240,196
Through "	1,914,430	981,944
Work train	107,624	107,624
Helper locomotives	225,474	102,111
Switching	397,000*	*397,000
Total freight, work, helper and switch	2,884,724	1,828,875
Total locomotive mileage	4,444,552	2,902,742
Locomotive ton mileage:		
Motor cars	000	83,307,600
Passenger locomotives	259,638,174	107,386,700
Freight locomotives	385,395,130	129,631,480
Work train locomotives	15,067,360	9,686,160
Helper locomotives	41,712,690	8,386,510
Switching locomotives	55,880,000	35,730,000
Total freight, work, helper and switch	498,055,180	183,434,150
Total all locomotives and motor cars	757,693,354	374,128,450
Ton mileage—cars and contents:		
Passenger trains	744,424,800	675,001,800
Freight trains	2,113,300,000	1,940,045,780
Work trains	40,560,000	40,560,000
Switching	158,800,000	158,800,000
Total cars and contents	3,057,084,800	2,814,407,580
Grand total ton-miles	3,814,778,154	3,188,536,030

*Six miles allowed for each hour a switch engine is in service.

Number of Locomotives Required

An examination of the records of numerous steam railroads will disclose the fact that a steam locomotive spends a good portion of its time in the shops undergoing heavy repairs. Also that a larger part of its time is spent in or near the engine houses where the boiler washing is done, the fire boxes and flues cleaned, and the light running repairs are made, etc. The records of two western steam roads show that their passenger locomotives spent respectively 21 per cent and 17 per cent of their time in the shops, and that the freight locomotives of the same roads were in the shop 30 per cent and 24 per cent of their time.

The most complete record of the actual distribution of engine service I have seen is given in Table VIII, which is for a section of a railroad between 500 and 600 miles in length.

TABLE VIII

	Passenger locomotives		Freight locomotives	
	Per cent of total time	Days per year	Per cent of total time	Days per year
Time in shops	22.4	82	28.2	103
Time spare	1.4	5	2.7	10
Time in enginehouse (having running repairs done, boilers washed, fire boxes cleaned)	53.2	194	35.9	131
Time running to and from trains	1.6	6	1.1	4
Time in helper service	1.1	4	4.3	16
Time on road	20.3	74		
Actually running			17.1	62
Standing on sidings, taking water, etc.			10.7	39
Totals	100	365	100	365

It will be noted that each passenger locomotive was actually on the road, running or standing on sidings, only 74 days of the year, while each freight locomotive, exclusive of those used for helper service, was actually running only 62 days of the year and standing on sidings, etc., 39 days, not considering the helper locomotives.

The number of locomotives required to handle the traffic of any railroad depends of course upon the quantity of traffic, number of trains, the arrangement of the train schedule, ratio of maximum and average traffic, etc. An estimate of the number of

steam locomotives required to handle the trains over the road can be made from the train sheets, and to this number will have to be added an allowance to cover time in engine house, shops, etc. as shown above in Table VIII. However, the total number of steam locomotives shown in Tables IX, X, XI and XII, as required for operating the railroad discussed in this paper, is the

TABLE IX
PASSENGER SERVICE

	Steam locomotives			Electric locomotives		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shops	22.1	81	6.2	19.2	70	2.5
Spare	1.4	5	0.4	3.1	11	0.4
In enginehouse, etc.	53.0	193	14.8	27.7	101	3.6
Running to and from trains	1.6	6	0.5	3.8	14	0.5
In helper service	1.5	5	0.4	3.1	11	0.4
On road	20.4	75	5.7	43.1	158	5.6
Totals	100	365	28	100	365	13

TABLE X
FREIGHT SERVICE

	Steam locomotives			Electric locomotives		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shop	28.0	102	26.9	25.1	91	10.8
Spare	2.7	10	2.6	6.0	22	2.6
In engine house	35.8	131	34.4	27.9	102	12.0
Running to and from trains	1.1	4	1.1	1.4	5	0.6
In helper service	4.8	17	4.6	3.5	13	1.5
Standing on sidings	10.6	39	10.1	13.7	50	5.9
Running on road	17.0	62	16.3	22.4	82	9.6
Totals	100.0	365	96.0	100.0	365	43.0

same as that actually used on a western railroad where the quantity of traffic and other conditions are similar. The number of electric locomotives given was estimated from the steam figures.

As there would be the same number of passenger trains, the number of passenger locomotives required (assuming all trains to

be locomotive trains) on the road would be the same for both steam and electric operation, except that, as no time would be used in taking water, a smaller number of electric locomotives would be needed on this road than by steam operation. There would be fewer freight trains by electric operation and, consequently, fewer electric freight locomotives would be needed than steam freight locomotives, in addition to the smaller number of electric locomotives required on account of not having to take water.

TABLE XI
SWITCHING SERVICE

	Steam locomotive			Electric locomotive		
	Per cent of time	Days of year	No. of locomotives	Per cent of time	Days of year	No. of locomotives
In shops	37.5	137	6	27.3	99	3
In service	62.5	228	10	72.7	266	8
Totals	100.0	365	16	100.0	365	11

TABLE XII
SUMMARY

	Steam Equipment	Electric Equipment
Passenger service:		
Motor cars	0	14
Passenger locomotives	28	10
Freight locomotives	96	43
Switching locomotives	16	11
Total motor cars	0	14
Total locomotives	140	64

The time in the engine house, where the inspection, cleaning and light repair work is done, will manifestly be much less with electric than with steam locomotives. A steam locomotive receives a thorough inspection after each run, whereas the practise with electric locomotives is to inspect them after they have made a certain mileage, which varies from 1200 to 2500 miles, the former figure being the New York Central standard, while the latter is the practise of the Pennsylvania Railroad at New York.

The boiler washing, fire box cleaning and other things required on a steam locomotive, and which consume a large part of the

time in the engine house, would not be necessary with electric locomotives and, consequently, the time spent by electric locomotives in or near the engine house would be much less than with steam locomotives. Likewise, electric locomotives would spend less time in the shops than steam locomotives, as there would be no boiler, firebox, smoke stack or tender to repair.

The above remarks, supplemented by Tables IX to XII inclusive, show how the number of electric locomotives needed to handle the given traffic was estimated.

Tables IX and XII show the number of locomotives and distribution of engine service for steam and electric operation of the 467-mile railroad being discussed.

Thus 13 passenger locomotives would be needed if all passenger trains were locomotive trains, but as electric motor cars are to be used for local passenger trains, only 10 electric locomotives would be needed for the through passenger trains, in place of 13 as shown in Table IX, but 14 motor cars would also be needed for the local passenger trains.

As a check on the above figures for number of locomotives required some data will now be given of electrified steam lines in operation. Table XIII below was computed and condensed from data given in a paper by Mr. W. J. Wilgus, Volume 61, A.S.C.E., concerning the electric operation of the N.Y.C. & H.R.R.R., and which, as I understand it, shows the distribution of steam and electric locomotive time out of the shop.

TABLE XIII

	Hours		Per cent	
	Steam locomotives	Electric locomotives	Steam locomotives	Electric locomotives
Busy	138.00	203.92	20.7	30.3
Waiting	174.10	229.19	26.2	34.2
Total	312.10	433.11	46.9	64.5
Dead	354.90	233.89	53.1	35.5
Grand total	667.00	672.00	100.0	100.0

These data, which are for all classes of locomotives, would indicate that for conditions on the New York Central the steam locomotives were having fire boxes cleaned, boilers washed,

light repairs made, and other things which are done in the engine house, a little over half the time out of the shops, while the time spent by the electric locomotives in the engine house being inspected, having light repairs made, etc., was only about one third of the time out of the shops.

Conditions on different roads are of course not the same, but I believe Table XIII shows that the estimates of number of electric locomotives for the 467-mile railroad here considered, given in Tables IX to XII inclusive, are very conservative in most items.

Estimated Cost of Electrification

The following is an estimate of the money needed to electrify the 467 miles of steam railroad considered:

High-tension lines (steel tower), 450 miles		$2,250,000
Trolley and feeder wire:		
3/0 grooved copper trolley, 468 mi. at $650	304,200	
Steel trolley wire, 156 mi., at $320	49,920	
2/0 feeder wire, 468 mi. at $500	234,000	
		588,120
Overhead construction:		
Bracket arm construction, 420 mi. at $1650	$693,000	
Span construction, 92 mi. at $2600	239,200	
Steel bridges, 4 mi.	36,000	
Section breaks	6,600	
Additional for curved track, 100 mi. at $300	30,000	
		1,004,800
Track bonding:		
624 mi. at $450		280,800
Substations:		
14 substations, 56,000 kv-a.	$616,000	
3 portable stations, 6000 kv-a. (complete)	96,000	
		712,000
Rolling stock:		
14 motor cars, $18,000	$252,000	
10 passenger locomotives, $45,000	450,000	
43 freight locomotives, $50,000	2,150,000	
11 switching locomotives, $35,000	385,000	
		3,237,000
Changing block signals and telegraph (468 mi.)		561,600
Engineering and supervision, 5 per cent		431,716
Contingencies, etc., 10 per cent		905,964
Total		$9,972,000
Credit for steam equipment:		
140 locomotives	$2,520,000	
241 coal cars	241,000	
14 passenger cars	112,000	
Give credit for, say, about 70 per cent of new value	2,873,000	2,012,000
Net estimate		$7,960,000

The figures given apply to the intermountain regions of the West. As the actual construction cost was available of a high-tension steel tower line parallel to a railroad, the material being distributed by work trains of the railroad, the estimate for this item given should be very close. The trolley line and substation estimates were based upon interurban construction cost of two lines in the West, a liberal allowance being made for the heavier work needed for trunk lines. No item is shown for electric shop machinery, as credit for steam locomotive shop machinery will offset this expense.

Comparative Cost of Maintenance and Operation by Steam and Electric Power

Having determined the amount of traffic of the railroad, and the number of trains necessary to handle it by steam and electric locomotives, the comparative cost of operation by steam and electric power will now be given.

While the bookkeeping methods are different on different railroads, the items into which the various maintenance and operating expenses are divided are the same, as the instructions of the Interstate Commerce Commission are followed. There are six general subdivisions into which the maintenance and operation expenses of a railroad are divided, as follows:

I. Maintenance of Way and Structures.
II. Maintenance of Equipment.
III. Traffic Expenses.
IV. Transportation Expenses.
V. General Expenses.
VI. Taxes.

The above headings are subdivided into numerous accounts. Traffic and General Expenses would not be affected by the kind of motive power and they will not be considered. For convenience in making the comparison between the steam and electric operating costs, the first heading will be divided into three parts and the second into two parts. The general headings will then be as follows:

A. Maintenance of Way and Structures.
B. Maintenance of Overhead Structures and Substations.
C. Depreciation of Overhead Structures and Substations.
D. Maintenance of Equipment.
E. Depreciation of Equipment.
F. Transportation Expenses.
G. Taxes.

The above headings are subdivided, as shown below, into 50 items or accounts. Tables XIV to XX below give the comparative steam and electric operating expenses of the 467-mile railroad considered.

TABLE XIV

MAINTENANCE OF WAY AND STRUCTURES

	Steam	Electric	Steam	Electric
	Per cent	Per cent		
1. Ties	100	92.5	$163,800	$151,515
2. Applying ties	100	92.5	46,800	43,290
3. Rail and other track material	100	85.0	93,600	79,560
4. Applying rail and other track material	100	85.0	32,760	27,846
5. Maintenance and care of track	100	85.0	154,400	131,240
6. Maintenance and care of roadbed	100	100.0	74,880	74,880
7. Signals	100	70.0	23,400	16,380
8. Telegraph	100	120.0	11,700	14,040
9. Engine house and shops	100	50.0	23,400	11,700
10. Fuel and water stations	100	0.0	23,400	000
11. Roadway tools and supplies	100	92.5	23,400	21,645
Totals			$671,540	$572,096

TABLE XV

MAINTENANCE OF OVERHEAD STRUCTURES AND SUBSTATIONS

	Steam operation	Electric operation
12. *Maintenance of trolley line:*		
Bracket construction, 420 mi. at $100	000	$42,000
Span construction, 92 mi. at $120	000	11,040
Steel bridges, 4 mi. at $60	000	240
13. Maintenance of high-tension line, 450 mi. at $50	000	22,500
14. Maintenance and inspection of substations	000	7,450
15. Track bonding, 624 mi. at $20	000	12,480
Totals	000	$95,710

TABLE XVI

DEPRECIATION OF OVERHEAD STRUCTURES AND SUBSTATIONS

	Steam operation	Electric operation
16. *Trolley wire:*		
Copper, $304,200 at 4 per cent	000	$12,168
Steel trolley, $49,920 at 5 per cent	000	2,496
17. Feeder wire, $234,000 at 1 per cent	000	2,340
18. Poles and fixtures, $968,000 at 5 per cent	000	48,400
19. Steel bridges, $36,000 at 3 per cent	000	1,080
20. Track bonding, $281,000 at 4 per cent	000	11,240
21. High-tension line, including copper, $2,250,000 at 2 per cent	000	45,000
22. Substations, $712,000 at 3 per cent	000	21,360
Totals	000	$144,084

TABLE XVII

MAINTENANCE OF EQUIPMENT

	Steam operation	Electric operation
23. *Passenger locomotive repairs:*		
Steam, 1,559,828 miles at 10c.	$155,983	
Electric, 1,073,867 miles at 4½c.		$48,324
24. *Freight and switching locomotive repairs:*		
Steam, 2,884,724 miles at 14c.	403,861	
Electric, 1,828,875 miles at 6c.		109,732
25. *Electric motor car repairs:*		
Electric, 971,922 miles at 3c.	000	29,158
26. *Passenger car repairs:*		
Steam, 13,661,220 mi. at 1.2c.	163,935	
Electric, 12,735,580 mi. at 1.2c.		152,827
27. *Freight car repairs:*		
46,500,000 car miles, at 0.6c.	279,000	279,000
28. *Coal cars (company coal):*		
3,850,000 car miles at 0.6c.	23,100	000
Totals	$1,025,879	$619,041

TABLE XVIII

DEPRECIATION OF EQUIPMENT

	Steam operation	Electric operation
29. Depreciation of locomotives, (steam, 3 per cent)	$75,600	
(electric, 2 per cent)		$59,700
30. Depreciation of motor cars, 2 per cent	000	5,040
31. Depreciation passenger cars released, 3 per cent	3,360	000
32. Depreciation coal cars released, 3 per cent	7,230	000
Totals	$86,190	$64,740

The steam operating expenses given in Tables XIV to XX are based upon actual steam railroad operation and the following remarks will show how the electric operating expenses were computed.

Ties. A comparison of the tie renewal cost of different railroads with different tonnage, at first glance, may seem to show no relation between tie renewals and ton mileage per mile of line. However, a careful study will show that upon railroads of light tonnage the tie renewals depend more upon how long the tie will last without rotting, while upon railroads of very heavy tonnage, it will be found that the ton mileage per mile of line is the most important factor in the tie renewals. The exact amount of tonnage which will cause the tie to wear out before it has rotted depends upon the character of the soil, kind of tie, whether treated or

TABLE XIX

TRANSPORTATION EXPENSES

	Steam operation	Electric operation
33. *Engine and motormen on switching locomotives:*		
Electric, 70 per cent of steam	$50,000	$35,000
34. *Engine and motormen on passenger locomotives:*		
Steam, 1,559,828 miles at 8c	124,786	
Electric, 1,073,867 miles at 8 c		85,909
35. *Engine and motormen on freight and work locomotives:*		
Steam, 2,262,250 miles at 11c	248,848	
Electric, 1,329,764 miles at 11c		146,275
36. *Enginemen and motormen on helper locomotives:*		
Steam, 225,475 miles at 12c	27,056	
Electric, 76,241 miles at 12c		9,149
37. *Car motormen:*		
462,820 miles at 2c	000	9,256
38. *Conductors and brakemen in switching service*	90,000	90,000
39. *Passenger locomotive train crews:*		
Steam, 1,485,550 miles at 6.8c	101,017	
Electric, 1,022,730 miles at 6.8c		69,546
40. *Motor car trainmen:*		
462,820 miles at 4c	000	18,513
41. *Freight and work train crews:*		
Steam, 2,262,250 train miles at 13c	294,093	
Electric, 1,328,764 train miles at 13c		172,739
42. *Fuel:*		
400,000 tons at $2.25	900,000	000
43. *Purchase of power:*		
90,000,000 kw-hr. at 0.75c	000	675,000
44. *Water*	52,000	000
45. *Lubricants*	14,000	6,000
46. *Other locomotive supplies*	23,000	16,100
47. *Engine house expenses, locomotives:*		
Steam, 40,000 locomotives at $2.50	100,000	
Electric, 14,000 locomotives at 80c		11,200
48. *Engine house expense, motor cars:*		
3,000 motor cars at 50c	000	1,500
49. *Signal operation*	40,000	35,000
Totals	$2,064,800	$1,381,187

TABLE XX

SUMMARY—OPERATING EXPENSES

	Steam operation	Electric operation
A. Maintenance of way and structures	$671,540	$572,096
B. Maintenance of overhead structures and substations	000	95,710
C. Depreciation of overhead structures and substations	000	144,084
D. Maintenance of equipment	1,025,879	619,041
E. Depreciation of equipment	86,190	64,740
F. Transportation expense	2,064,800	1,381,187
G. Taxes		31,551
Totals	$3,848,409	$2,908,409

Steam operation expenses	$3,848,409
Electric operation expenses	2,908,409
Annual saving effected by substitution of electric power	$940,000

untreated, and a number of other varying quantities, and therefore can hardly be definitely determined for all conditions. In the table above, it was assumed that 50 per cent of the tie renewals was proportional to the ton mileage per mile of line, while the other 50 per cent was not affected by the tonnage. As the electric ton mileage was only 85 per cent of the steam ton mileage, the estimate of the electric tie renewal cost was (85 per cent $\times$ 50 per cent + 50 per cent) = 92.5 per cent of the steam tie renewal cost.

Rail and Track Maintenance. Experience has shown that the wear and tear on the rails, fastenings and other track material, as well as the cost of the maintenance and care of the track proper, varies according to the traffic handled over the road. Also the locomotives, on account of the greater weight on the axles, have been found to cause more damage to the track per ton than the cars. As there is less ton mileage per mile of line by electric operation than by steam, on account of the electric locomotives being lighter and fewer being necessary, as fewer electric freight trains are operated, it is reasonable to expect that the damage to the track will be much less by electric operation than by steam operation. It has been definitely shown in steam operation that if a larger steam locomotive is continuously operated over a division, additional labor will be required on the track of that division. The cost of rail and other track material and the maintenance and care of the track in above estimates was assumed to be directly proportional to the ton mileage. The greater damage per ton by the locomotive was ignored, as it was desired to make a conservative estimate.

Maintenance and Care of Roadbed. This account includes such items as cleaning ditches, sloping cuts, removing slides, cutting weeds, protection of the roadbed from water, etc., and will not be affected by electric operation. It is included in the above table and mentioned here in order that it will not be confused with the track maintenance.

Signals and Telegraph. The cost of the signal system maintenance, which by steam operation is operated by storage batteries, would be considerably reduced, as no battery expense would be necessary, while on the other hand the telegraph line maintenance would cost more, on account of the interference of the trolley and high-tension line circuits.

Engine Houses and Shops. This expense will be much reduced by electric operation, both because there will be no smoke and gases to contend with and because fewer electric locomotives will be handled.

Locomotive Fuel and Water Stations. These items will, of course, not be necessary for electric operation. However, if water-cooled transformers are used, a portion of the water station expense will be necessary.

Roadway Tools and Supplies. Half of this item is assumed to be independent of electrification, the other half is assumed to vary as the ton mileage, as the track maintenance expenses will be greater if the traffic is greater, and by electric operation the ton mileage would be less than by steam operation.

Maintenance of Overhead Structures. The typical arrangement of the overhead structures proposed, where there are no yards, is to have high-tension steel tower line paralleling the track and the bracket arm type of trolley construction, with wood poles and one feeder wire. The figure of $150.00 per mile used to cover the maintenance and inspection was based upon the present cost of steel tower, wood pole and interurban trolley line maintenance in this western section, an allowance being made for the more expensive maintenance cost of the heavier construction needed on a trunk line railroad. The same men are to be used to look after both the high-tension and trolley lines. The figures given above for the span and steel bridge construction were estimated in like manner.

Maintenance of Substations. No attendants were considered necessary, as it is assumed that the inspection and light maintenance could be done by the linemen. In case of accident, the trouble department would take hold, as is now done by the wrecking crew on steam railroads, portable substations being provided in case of a complete shut-down.

Depreciation of Overhead Structures and Substations. In addition to the maintenance of the overhead structures and substations there is also the depreciation and renewal expense, and Table XVI shows the percentage used in this estimate.

Locomotive Repairs. Experience has shown that the repair expense of an electric locomotive is much less than that of a steam locomotive, which should be the case, as there is no boiler, firebox, smoke stack or tender on an electric locomotive, as has been stated before.

Also, there are operating factors entering into the repair cost which should be considered. Table XXI below gives some cost data of a Western railroad, which will be useful in showing the effect of different operating factors on the repair expense.

TABLE XXI

Class of locomotive	Total weight with loaded tender (tons)	Weight on drivers pounds	Average number of locomotives	Number of years record	Miles per year per locomotive	Annual repair cost of each locomotive	Repair cost per locomotive mile
Passenger locomotives, Atlantic type	165	105,000	11	8 yrs.	60,500	$4200	6.95c
Passenger locomotives, Pacific type.	192	141,000	7	8 yrs.	65,100	5550	8.52c
Freight locomotive Consolidated simple type.....	159	178,000	5	9 yrs.	23,500	2500	10.67c
Freight locomotive consolidated simple type.....	185	187,000	63	5 yrs.	30,300	3845	12.69c
Helper locomotive Consolidated compound type.....	155	165,300	15	6 yrs.	14,500	2785	19.21c
Switch locomotive 10-wheel type.....	110	140,000	13	9 yrs.	In service 4750 hours per yr.	1950	——

The above figures are averages of several years, but since the cost of both labor and material has greatly increased during the last few years, the averages shown are somewhat less than what the actual cost now is. The annual repair cost of the high-speed steam passenger locomotives is shown above to be much higher than the low-speed freight locomotives, but the locomotive-miles per year of the passenger locomotives is so much greater than the annual mileage of the freight locomotives that the cost per locomotive-mile—which is really a measure of the cost of train operation—is considerably less for the passenger locomotives. It will also be noted that the repair cost seems also to vary with the weight of the locomotive, and especially the weight on the drive wheels.

The high cost shown for the helper locomotives resulted from three causes. The annual mileage was very low. The engines were used on the maximum grades and consequently when ascending these grades were stressed to their maximum and also required full braking when descending these heavy grades. The more complicated mechanism of compound engines is also more expensive to maintain than that on simple engines.

Thus the cost of locomotive repairs varies according to kind

of service, class of engine, grades, mileage, etc. A study of the repair cost details shows that they are in many cases affected by local conditions. Thus the kind of water available, especially in some sections of the West, where considerable alkali water is present, may cause the boiler maintenance expense to become very large. The following is an estimate of the relative repair cost of steam and electric locomotives for the road considered, it being assumed that only a small amount of alkali water is used in the locomotives.

	Locomotive repair expense	
	Steam	Electric
	Per cent	Per cent
Boiler, firebox, tender, smoke stack	38	0
Running gear and machinery	62	45
Total	100	45

The steam locomotive percentages segregated above were estimated from a study of the details of the repair expense of one railroad with conditions similar to the road here considered. The method of keeping the records made it impossible to get an absolute segregation of the costs, but I believe the above is a fair estimate. The electric locomotive percentages were estimated from the steam records. The running gear repair expense was considered the same for both locomotives. The maintenance expense of the control apparatus and electrical equipment is not high on most modern electric locomotives, and it is reasonable to expect it to be less than the steam machinery costs, and it was considered so in the above estimated segregation. The painting and other miscellaneous expenses will not be any greater with an electric locomotive and probably will be a little less. The final results consider the electric locomotive repair expense to be only 45 per cent of the steam locomotive repair expense for the road here considered. The reliability of this estimate will now be checked by giving some actual figures of the relative repair cost of steam and electric locomotives.

The published figures of the N.Y.C. & H.R.R.R. (Vol.61, A.S.C.E.) show that the steam locomotives cost $1842.00 for repair during 335 days, while the electric locomotives only cost, during 350 days, for the same service, $704.00. The electric locomotive repair cost on the N.Y.C. & H.R.R.R. is thus only 36.5 per cent of the steam locomotive repair cost. Another

set of published figures gives for 1908 the cost per locomotive-mile as 2.83 cents for New York Central electric locomotives, and between 26,000 and 27,000 locomotive-miles as the annual mileage of 35 locomotives. The Interstate Commerce Commission records for 1908 show 8.2 cents per locomotive mile for all steam engines of the N.Y.C. & H.R., with annual mileage of 28,950 per locomotive, the annual passenger locomotive mileage being 38,400 and the annual freight locomotive mileage being 21,000 per locomotive. The cost per locomotive-mile segregated between passenger and freight service was not given. The 1912 New York Central electric locomotive repair cost published is 3.34 cents per locomotive-mile.

The figures published by Mr. Gibbs of the Pennsylvania R.R. give the electric locomotive repair cost as 5.91 cents per locomotive-mile, the New Jersey Division steam locomotive repair cost as 8.83 cents per locomotive mile, and the average of steam locomotives for all divisions of the Pennsylvania as 11.9 cents per locomotive-mile. The electric locomotive repair expense is thus only 67 per cent of the steam expense on the New Jersey Division and only 50 per cent of the steam repair expense on all divisions. The annual mileage of the electric locomotives was 26,000, 28 per cent of which was switching. The steam mileage is not given, but from Interstate Commerce Commission reports for 1910 it is shown as 27,610 for the whole road.

The extremely heavy grades on the electrified section of the Pennsylvania railroad of course make the repair cost of the electric locomotives considerably higher than if they were operated over a section with the grades as low as the average of the whole road, and consequently the relative cost of steam and electric locomotive repairs will be even less than shown. The electric locomotives of the P. R.R. are also much more powerful than the steam locomotives.

All things considered, it is probable that the electric locomotive repair cost will be even lower than 45 per cent of the steam locomotive repair cost, which was estimated above for the road considered, and used in making the comparative estimate of steam and electric operating expenses. For the road considered, the repair expense for steam passenger locomotives was taken at 10 cents per locomotive-mile, and steam freight, helper and switching locomotives 14 cents per locomotive-mile, which figures were based on the present locomotive repair costs on a Western railroad where similar conditions exist. The electric locomotive repair

expense will thus be 4.5 cents per locomotive-mile for passenger locomotives and 6 cents per locomotive-mile for freight service. The helper locomotives are more expensive to maintain than road engines, but, on the other hand, the switching locomotives cost less. The freight, helper and switching locomotives were combined in order to simplify computations.

Electric Motor Car Repairs. There are numerous data available on the repair cost of motor cars and 3 cents per car-mile, exclusive of inspection, which is included under the head of engine-house expenses, was used in the above estimate.

Passenger and Freight Car Repairs. These items will decrease by electric operation, as some passenger cars would be released by the use of electric motor cars, and in like manner the freight car repairs account is decreased by electric operation on account of no coal cars being used for hauling locomotive coal, as power is purchased.

Depreciation of Locomotives. An electric locomotive will have a longer life than a steam locomotive, and thus the rate of depreciation will be less. However, the electric locomotive usually costs so much more than a steam locomotive that the actual depreciation charge per locomotive is generally greater in the case of the electric locomotive. On the other hand, the number of steam locomotives required to handle a given traffic is in most cases much greater than the number of electric locomotives required and, consequently, the total depreciation is generally greater for steam operation. The statement below shows the depreciation percentages used in the above tables. The steam locomotive figures were obtained from the auditing department of a western line. The electric figures were estimated, and although the modern electric locomotive has been in use only half the time allowed below for its life, I think past experience justifies the expectation of the life allowed. In any case, I do not believe there is any question as to the relative life of steam and electric locomotives.

	Steam locomotive	Electric locomotive
	Per cent	Per cent
First cost of locomotive	100	100
Salvage value when worn out	20	30
Total cost	80	70
Estimated life	26⅔ yr.	35 yr.
Annual depreciation	3%	2%

Depreciation of Passenger and Freight Cars. The following statement shows the methods used and the percentages estimated for these items:

	Passenger cars	Steel freight cars
	Per cent	Per cent
First cost	100	100
Salvage value	15	20
Total cost	85	80
Estimated life	28½ yr.	26⅔ yr.
Annual depreciation	3%	3%

Enginemen and Motormen. The wages of the motormen on the electric locomotives were assumed to be the same as those of the enginemen on the steam locomotive, but the motormen on the electric motor cars were taken as equal to about what would be paid for trolley car service. Although no fireman is needed on electric locomotives, two men were assumed necessary for all electric road and helper locomotives; but on switching locomotives, which have a conductor, and sometimes two or three switchmen, only a motorman was allowed. When two electric locomotives are used on a helper district to assist the road locomotive, only one crew was allowed, as the electric helper locomotives, being equipped with multiple-unit control, can be operated by one crew.

Trainmen. The reduction in this item is caused by operating fewer freight trains and in the case of the motor car trains a smaller train crew will be required than in the case of a steam train.

Fuel Expense. All coal used on a steam locomotive is not utilized in hauling trains but a good deal is wasted by radiation while the locomotive is standing on sidings, imperfect combustion in the firebox, starting fire, etc., and the loss of energy is very much greater than would be the case in a steam-electric plant generating power for electric operation of a railroad. The figures published by Mr. W. S. Murray in a discussion* in November, 1907, indicate that it requires about double the coal for operation of the steam locomotives of the N. Y. N. H. & H. R.R. that it does to generate power in a steam-electric power plant for operation of its electric locomotives in the same service.

There are few railroads where coal is obtained for less than from $2.00 to $2.25 per ton and some pay more than double the high-

*Trans. A. I. E. E., Vol. XXVI, 1907, p. 1680.

est figure mentioned. For the road here considered, coal will be estimated to cost $2.25 per ton and be delivered at terminal No. 4.

The quantity of coal is the same as the actual amount used on a steam railroad for all classes of service where conditions are similar to those here discussed.

The hauling of the locomotive coal over the railroad's own line is a very important item, as it amounts to 174,000,000 ton-miles, as it was assumed to be delivered to the railroad at terminal No. 4 at the east end of the line. In this connection, attention should be called to the fact that if some section of the railroad toward the west was considered for electrification, the cost of hauling the coal over the other portion of the line should properly be considered in connection with electrification estimates. For the case here considered, the cost of hauling the coal is taken care of by allowing fewer train-miles, fewer locomotive-miles and fewer ton-miles, in the figures given for electric operation.

Electric Power. The quantity of electric power needed was computed from the grades, train weights, speed and other necessary data. The average power for a train of two motor cars and trailer, making stops every six or eight miles, was taken at 40 watt-hours per ton-mile. The passenger locomotive trains were allowed 31 watt-hours per ton-mile. The freight trains were allowed 25 watt-hours per ton-mile and the switching locomotives were allowed 45 watt-hours per ton-mile.

As stated above, the power is to be purchased and delivered into the railroad's high-tension transmission line at terminal No. 3. The rate to be paid for electric power in any locality depends upon the local conditions, the load factor, cost of coal, etc.

The load factor on most of the present electrically operated railroads is generally very low. This will not be the case when the long trunk lines of railroad are electrically operated, as the heavy through passenger and freight trains operate night and day, and although there will be peaks in the load curve, I am inclined to believe that the power required to operate the railroad during different times of the day or year will be surprisingly uniform.

As an example, take the railroad considered: The greatest number of trains upon the line at one time on the maximum day of the year would be four motor car passenger trains, five through passenger trains and 18 freight trains. Some of these would be operating against grades and others would be running down grades. The maximum power on five-minute peaks for operating these trains should not exceed about 20,000 horse power. The average

load for the year would be 13,700 horse power. Considering the annual load factor equal to the ratio of the average load of the year to the maximum five-minute peak, the annual load factor for the above railroad would thus amount to 68.5 per cent. Allowing for emergencies and delayed trains, the load factor should not get lower than 60 per cent.

On the basis of coal at $2.25 per ton and a load factor of 60 per cent, there should not be much trouble in purchasing electric power at 0.75 cent per kw-hr., which figure was used in above estimates. However, at most points, a very high grade of coal is required for use on the locomotives, whereas a steam-electric plant can be designed so that slack or any of the low-cost grades of coal could be used. In the intermountain section of the West, the cost of slack coal is less than half that of run-of-mine coal, which is used for locomotives, and in a steam plant slack coal is nearly as efficient as run-of-mine coal.

In many sections of the West, the development of numerous hydroelectric plants at extremely low construction cost has made it possible to obtain power at some points at considerably lower cost than 0.75 cent per kw-hr., which was used in the above estimate. For instance, the Great Falls Power Company has made a rate of 0.536 cent per kw-hr. to the Chicago, Milwaukee & Puget Sound Railway, and agrees to construct some of the high-tension lines.

Engine House Expenses. The steam engine house expenses would be very much reduced if the road were electrically operated, for two reasons. There would be fewer inspections necessary with electric locomotives, and the nature of the engine house work is such as to require much less expense with electric locomotives, as there is no boiler washing, firebox cleaning, ash pit expense, etc., with electric locomotives.

It is customary to clean the firebox and give the steam locomotive a thorough inspection after each run, although boiler washing is only done after two or three runs, depending upon the quality of the water obtained. The practise with electric locomotives is to give them an inspection after a certain mileage, which ranges from 1200 to 2500 miles on different roads, as explained before. For the road here discussed, an allowance was made for an inspection of the electric locomotives after every round trip, which would mean an inspection after the locomotive had made a little over 300 miles. Possibly this allows too high an expense for the electric locomotive, but the estimates will be conservative.

It would be necessary to handle through the engine house at the terminals annually about 40,000 steam locomotives, or 14,000 electric locomotives, which in both cases contains an allowance for contingencies which always happen. Fewer electric locomotives are handled also because there are fewer electric than steam trains.

The cost per steam engine handled varies according to local conditions and other things. In the above estimates $2.50 per steam engine handled was allowed, which is based on actual operation costs where conditions are similar to the road discussed. The details of this, together with the estimated cost of handling electric locomotives, are shown in Table XXII below.

TABLE XXII

ENGINE HOUSE EXPENSES

	Steam locomotives	Electric locomotives
	Per cent	Per cent
Engine house foreman	1.3	1.3
Electric inspectors	0.0	2.0
Hostlers and helpers	7.0	6.0
Engine crew callers	2.3	2.3
Wiping and cleaning	16.7	11.7
Boiler washout	42.2	0.0
Cleaning flues	3.6	0.0
Stack inspectors	1.0	0.0
Supply men	2.7	2.7
Firing up engines	2.8	0.0
Sanding engines	1.3	1.2
Turntable (hand)	5.4	5.1
Sweeping engine house	1.2	1.0
Fueling engines	2.4	0.0
Cleaning fire boxes, etc.	5.4	0.0
Cleaning ash pits	4.7	0.0
Totals	100.0	33.3

Thus it is estimated that it only costs one-third as much to handle an electric locomotive through the engine house as it takes to handle a steam locomotive. At $2.50 per locomotive for steam operation would mean about 80 cents per locomotive for electric operation.

The New York Central figures published by Mr. Wilgus in Vol. 61, A.S.C.E., give $3.37 per day for steam locomotives and 55 cents for electric locomotives, or the electric cost of engine house expenses only 16.3 per cent of the steam.

Return on Investment

The estimated cost of the electrification of the 467-mile railroad considered above was $7,960,000. The return on this investment on account of the saving in operating expense was estimated at about $940,000 per year. The interest earned on the money used for the electrification of this road would thus be 11.8 per cent. If it is necessary to borrow the money for this purpose, and if it can be obtained at 5 per cent interest, there would remain a profit to the railroad of 6.8 per cent of the net cost of electrification.

Besides this increase in the railroad's revenue, it will generally be possible by operating a frequent local passenger train service with frequent stops to increase the passenger earnings and add considerably more money to the net revenue of the railroad. There are very few localities where local passenger trains are now operated which would not at least add $500.00 per year per mile of line to the gross revenue if frequent interurban cars were substituted for the local steam train. This, of course, will depend upon the density of the population, local conditions, etc. However, the increase in passenger revenue may, under the conditions in many localities, amount to several thousand dollars per year per mile of line, and is a very important consideration wherever electric operation is proposed. At the rate of only $500.00 for the 467-mile railroad considered, the increased passenger revenue would amount to $233,500.00 per year, which would add materially to the revenue resulting from electrification.

Conclusions

As stated at the beginning, the great objection to the electrification of steam railroads is the heavy expenditure involved, while the chief reason for considering the electric operation of steam railroads, aside from some special conditions at local points, was to increase the net earnings of the road. It was further stated that the answer to the question of whether the increased net earnings which would result from the electric operation would be great enough to pay interest on the cost of electrification, and besides leave a profit, could only be had by making a careful investigation of each individual road.

The example taken above was not chosen to favor electric operation but was taken to show actual conditions. It will be noted that the quantity of traffic assumed was comparatively small, which of course does not favor electric operation. The

data given above, which will be found similar to those on many steam railroads, show that the traffic on many of the trunk railroads now operated by steam locomotives could be more economically handled by electric locomotives. The fact that, electrically operated, the road considered above could handle the same traffic with about 25 per cent less train mileage and locomotive mileage than when operated by steam, and with 15 per cent less ton mileage and about half as many locomotives as are needed for steam operation, is certainly deserving of serious consideration.

The overload characteristic which makes it possible for the electric locomotive to haul heavier freight trains over the short heavy grade sections than can be done by steam locomotives was illustrated above, and would indicate that considerable money now expended upon grade reductions of steam railroads would not be warranted if the road were electrically operated.

There has been considerable discussion lately as to the advisability of each railroad company building a power plant of its own, or else purchasing power from a central power company for railroad operation. One advantage of purchasing power is that the load factor of the large power companies' plants is usually high, whereas on most railroads now operating by electric power the load factor of the railroad power plants is generally low and, consequently, cost of generating power in the railroad plants is high. However, on the other hand, the load factor of a long trunk line will probably be high and the advantage of high load factor in a power company's plant will in many cases disappear.

The most important advantage in favor of railroads purchasing power for electric operation is that the heavy investment necessary for electrification would be reduced. It appears to me that the relative advantages of purchasing or generating electric power will have to be determined by local conditions. The competition between various railroads would, of course, be a very important consideration and is probably one of the principal objections to the purchasing of power from central stations. However, if a long time contract could be made with a power company at a low rate, it would have many advantages.

Another important point is suggested in connection with the electrification of steam roads and supplying electric power for them, which should be mentioned before closing this paper. At many points in the country, large steam-electric central stations

have been constructed and at the present time the amount of coal hauled from the mines to these central stations has become very large. It is also absolutely necessary that nothing delay the delivery of coal to the central stations, as the business of a whole community could be easily tied up if the electric power supply were cut off. Consequently, if in providing for future power at such points as Chicago and New York, steam-electric plants be constructed at suitable points in the vicinity of the coal mines of Indiana, Illinois and Pennsylvania, and high-tension lines be constructed from these new plants to Chicago and New York, the providing of additional railroad facilities for power plant coal hauling would not be necessary. Also, the present steam plants would insure a power supply at the distributing points during the short interruptions which occur on high-tension transmission lines.

The advantage of this arrangement to the railroads would be that if the high-tension lines were constructed upon the right of way of the railroad lines, the railroads could obtain electric power for their substations, when the roads were ultimately electrified, without the heavy expense of constructing high-tension lines of their own. The question as to whether the railroads should own the whole or a part of the power companies, is, of course, a matter which will have to be determined by local conditions.

Where water power is plentiful, as is the case in many sections of the West, the advantage of being able to tie in isolated hydroelectric plants, located at points where there is only a small market for power, to a network of high-tension lines on the railroad rights of way extending to localities where there is a market for power, is evident. Also the chief objection to the electrification of steam railroads (the heavy first cost) would be made of less importance by this arrangement.

DISCUSSION ON "2400-VOLT RAILWAY ELECTRIFICATION" (HOBART) AND "TRUNK LINE ELECTRIFICATION" (KAHLER). NEW YORK, MAY 20, 1913.

A. H. Armstrong: The two papers presented before the Institute at this meeting arrived at the same happy conclusion as to the benefits to be secured in the electrification of steam roads, but differ as to the means of securing this end. In other words, one paper advocates the single-phase and the other the direct-current motor. Instead, therefore, of following the usual procedure of side-stepping the question of single-phase versus d-c., I will confine my remarks to a broad discussion of this question as affecting the general subject of electrification.

We seem to be entering an era of electrification of steam roads, and perhaps the enthusiast for single-phase alternating trolley operating at high potential may be unduly influenced in drawing his conclusions by reason of the small tonnage carried on some of the lines where electrification is proposed. A high-voltage trolley means a minimum expense for copper and substations, but an increased cost of motive power. Looking at the matter broadly and considering that the investments made today should be based upon taking care of the traffic of to-morrow, it is reasonable to figure the first cost of electrification of any given road on the basis of an increase of 50 per cent or 100 per cent over the present tonnage now carried.

It is a well known fact that the cost of locomotives equipped with single-phase a-c. motors is higher than that of locomotives equipped with direct-current motors capable of doing similar work. When the total expense for motive power is small, that is, when the road is carrying a small tonnage and trains are infrequent, the high cost of locomotives does not become burdensome, but with increase in traffic continually demanding larger investment in motive power, the handicap of the single-phase motor is more keenly felt, and may soon overbalance the apparent initial saving in feeder copper and substation expense required with the use of the direct-current motor. On the other hand the substation and line copper expense is more or less proportional to the tonnage and speed of the moving train and is seldom influenced by the frequency of this train service. In other words, the capital invested in substation and feeder copper to take care of the movement of ten 2500-ton trains per day is generally great enough to permit the movement of twenty trains per day of equal tonnage. The feeder copper and substation installation therefore constitutes more or less of a fixed capital investment subject to a slight increase with increase in tonnage, while the locomotive investment increases with the tonnage, or even faster when track congestion commences to be a factor. We are quite liable, therefore, to turn the apparent saving of to-day into an increasing burden of expense in the future with the increase in tonnage which may be expected on our trunk lines. Should the selec-

tion of the single-phase system be based upon the apparent saving in first cost with present tonnage, the same reason may not hold if based upon the same road, carrying double the tonnage. In other words, in balancing substation and feeder copper expense against locomotive expense we are comparing what is more or less of a fixed investment against one that will increase in due proportion to future increased tonnage.

The company with which I am associated, in common with other investigators, has been for several years developing a piece of apparatus known as the mercury vapor rectifier, and the successful development of this rectifier will open up increased possibilities which we hope will accelerate the electrification movement. When developed, the rectifier affords the most efficient means known of changing from alternating to direct current. The glass tube of 10 or 15 kw. has expanded into a steel rectifier of over 1000 kw. as it stands developed to-day, and no immediate limits are in sight as to the ultimate capacity of this piece of apparatus. While the rectifier is still in the laboratory stage so far as its actual commercial use is concerned, it holds promise of being available in the immediate future and its success will have a bearing upon the electrification work of the future.

There are two methods of using the rectifier.

First, it can be placed upon a locomotive equipped with direct-current motors and transformer used in connection with 11,000-volt single-phase trolley distribution system. In this case the rectifier will operate single-phase, will produce a current that is unidirectional, but the pulsating character of the current may demand special construction of the d-c. motors. The single-phase step-down transformer will also be special in character in order to provide for the needs of the rectifier.

In general the advantage offered by the use of the rectifier on the locomotive lies in the possibility of using direct-current motors instead of single-phase, and thus obtaining the admittedly better constants of that type of motive power. I know no authority who will question the superiority of the direct-current motor over the single-phase a-c. motor as applied to traction work, and the rectifier placed upon the locomotive itself combines the good qualities of the d-c. motor on the locomotive with all those advantages claimed for the single-phase high-tension trolley distribution.

Second, the rectifier may be placed in substations located at the most desirable points along the right of way. In this case the rectifier will use balanced three-phase energy of any frequency, taking energy equally from all three legs of the circuit, and by using a multi-phase rectifier it will result in giving direct current in which the fluctuations are largely eliminated. This will enable such a rectifier substation to feed standard direct-current motors and will moreover provide a balanced three-phase load which can be supplied from existing transmission

systems at any frequency without causing undesirable interference with lighting and miscellaneous load distribution. The general advantage of locating the rectifier in the substation is that its efficiency will probably be from 10 to 15 per cent higher than that of a motor-generator set, and furthermore the rectifier is adapted to deliver direct-current energy of any potential required and is therefore admirably fitted to supply 2400 volts or higher to the trolley. Furthermore, the substation, being without moving machinery, can be operated with a minimum of attendance and may show an attractive reduction in first cost over motor-generator set substations.

Introducing the rectifier substation upsets our preconceived ideas as to the proper relation of cost of substation and feeder copper, as the rectifier substation shows a very marked increase in efficiency, decreased cost of complete substation, and we may even anticipate the time when it can be operated without attendants in such localities as would require no attendance with a a step-down transformer station. The success of the rectifier therefore means just as much to the high-voltage direct-current motor system as to the single-phase trolley.

In conclusion, it seems to me that, looking at the matter broadly and without enthusiasm but with full knowledge of the operating facts of to-day and the possibility of the immediate future, the single-phase commutating motor as such is destined to become more or less a thing of the past. It is even a grave question whether the single-phase trolley locomotive of any description, with its interference with neighboring telephone and telegraph lines, the difficulty and expense of providing single-phase current without erecting a generating and distributing system devoted solely to railway apparatus, and with the high first cost and cost of maintaining the motive power, do not all together present difficulties which make the single-phase trolley system undesirable, viewed from the standpoint of the high-voltage direct-current motor and its possibilities.

While the Butte, Anaconda & Pacific direct-current locomotive was designed and is now in commercial operation at 2400 volts, the company constructing it also built and tested high-potential direct-current apparatus up to 5000 volts with entire success, and no objection can be raised as to the practicability of using this high potential if local conditions demand it.

As a final remark I wish to state that as evidence of the possibility of having the mercury rectifier available in the near future, there was run at Schenectady during the past week a test with one of the Butte, Anaconda & Pacific 80-ton locomotives and a 1000-kw. mercury vapor rectifier, during which test no restrictions whatever were placed upon the motor output, such as operating at full load, slipping the wheels, etc. It is probable that within a few months there will be equipped for demonstration both a locomotive and a stationary substation containing mercury rectifiers which will be put into commercial

operation to secure the active experience needed to make this type of apparatus commercially available.

F. E. Wynne: In going over Mr. Kahler's paper I noted his tables on the division of time for steam and electric locomotives, Tables IX and X, and thought it would be useful to plot these (Figs. 1 and 2) so as to show at a glance what might be not apparent in these tables without study. The values for steam are actual results, and those for electric locomotives are Mr. Kahler's estimates.

The top section in each figure represents the time on the road; the bottom section represents the time spent in the engine house. It is interesting to note that for the passenger locomotives these sections are approximately reversed for electric and steam operation. On the freight engine the difference is not so great, although the electric engine makes considerable gain over the steam. In the freight diagram there is a certain area representing the time spent in sidings; in other words, the loco-

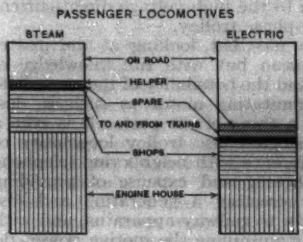


FIG. 1

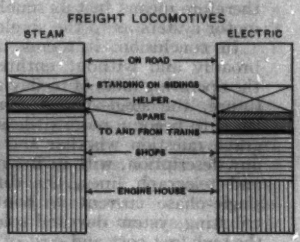


FIG. 2

motives are ready for operation but are not in actual motion on the road.

Mr. Kahler has used an electric locomotive of much greater hauling capacity than his steam engine. The steam engine weighs a total of 185.1 tons with loaded tender, and has a maximum tractive effort of 43,000 lb. The electric locomotive weighs 110 tons, all weight on drivers, and has a maximum tractive effort of 55,000 lb. Applying these tractive efforts to show what can be done on short ruling grades, I have worked out Fig. 3, for grades from level to a maximum of 4 per cent, showing the ratio between the maximum tonnages which the electric and steam locomotives can haul. On level track the electric engine hauls 38 per cent more than the steam engine, and on a one per cent grade approximately 50 per cent more. Grades up to 4 per cent are shown because such grades occur on branches of existing steam roads. Fig. 3 is based on train friction of 6 lb. per ton for trailing load, 15 lb. per ton for the electric locomotive and 25 lb. per ton for the steam engine.

Mr. Kahler's paper refers to gasoline motor cars and gasoline-electric motor cars. In this connection I think it is well for us to remember that most of the comparisons which have been made between steam locomotive operation costs and the costs of these self-contained motor cars have considered everything in figuring out the cost with steam, while in giving the cost of the self-propelled units nothing is included for track maintenance, signaling, despatching, or general expenses. So the comparison is not always a fair one.

I was very much interested in the table in which Mr. Kahler shows the limiting grades for both electric and steam operation, and where he shows the tonnage which can be handled in the various districts with each type of engine.

I think the chief value to be found in Mr. Kahler's paper, aside from the actual records of steam operation which he has submitted, is the fact that he has shown the way to attack the problem of ascertaining whether it will pay to electrify a steam road; he has shown how to analyze steam operation and estimate the probable saving by electric operation. His results are very interesting, showing, for electric operation, an annual saving of $940,000.00, on a net investment of approximately $8,000,000.00 or a gross investment of approximately $10,000,000.00. In other words, if we take account of the salvage for steam locomotives, the return on the investment is approximately 11½ per cent, or, if the steam locomotives are worn out and there is no salvage at all, we still have 9½ per cent.

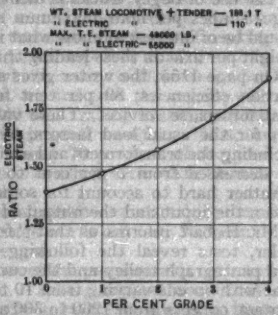


FIG. 3—RELATIVE HAULING CAPACITIES OF ELECTRIC AND STEAM LOCOMOTIVES ON SHORT RULING GRADES

Table XXI, page 1216, throws some light on the estimate of locomotive maintenance made by Mr. Hobart. The figures given in Table XXI show that maintenance is largely affected by the class of traffic in which the locomotive is used. In high speed traffic, where the mileage is great, the cost per engine mile is lower than with low speed service. With the exception of those for the helper engine all of the figures given by Mr. Kahler are below 10c. per mile per 100 tons of engine; the passenger engines show between 4c. and 5c. and the freight engines between 6c. and 7c.

In Table XXII, a most interesting item is that boiler washout requires 42 per cent of the steam locomotive's engine house expenses.

In connection with Mr. Hobart's paper, I have noticed some things which steam railroad men may see, and, knowing they are somewhat unusual for steam operation, may be led to doubt the value of other figures in the paper.

On page 1153, for a certain class of engine and train, the pounds of coal per drawbar horse power-hour are determined. When converted into other units it shows, on a basis of 14,000-B.t.u. coal, the gross ton-miles hauled are 7.6 for each pound of coal; and, on a basis of 11,000-B.t.u. coal, 6 gross ton-miles for each pound of coal burned. These values, I believe, are rather high, even in passenger service, as I have some records of steam operation which show that this figure for both freight and passenger services is between three and a quarter and four gross ton-miles for each pound of coal burned.

The use of bogey trucks is mentioned for locomotives exceeding 45 miles per hour maximum speed. In this connection it would be of interest to know what is considered the limit of dead weight per axle on these leading trucks.

On page 1155, the writer gives some rather high over-all substation efficiencies; 89 per cent for dense service and 78 per cent for sparse service. These values are high, and if worked out for the usual load factors, with motor-generator sets and including the transformers and exciters, these percentages would be decreased from 7 per cent to 10 per cent. Otherwise, it is rather hard to account for some of the large differences between the input and the output of substations on actual roads.

Mr. Hobart informs us that "for a given life of the contact roller, tests reveal the following relation between the speed of a pantagraph trolley and the current which can be collected," that with speeds varying from 10 to 60 miles per hour the roller contact collects from 1200 to 300 amperes, respectively. These figures seem very high, and it would be very interesting to the Institute to know what life of the contact roller can be secured with a roller collecting these currents at these speeds, as the roller is somewhat expensive to renew.

The paper contains an apparent inconsistency in that 34,000 lb. is taken as the drawbar pull for two of these Butte, Anaconda & Pacific locomotives, and the corresponding speed is taken at 14 miles per hour. On the next page the continuous tractive effort is given as 25,000 lb. each, or a total of 50,000 lb., at 15 miles per hour. Evidently this speed of only 14 miles per hour at 34,000 lb. drawbar pull takes account of the large line drop that goes with a direct-current installation. On the other hand, when it comes to estimating the current to be collected, 2400 volts at the locomotive is the assumed voltage.

If the speed curve of this particular locomotive were available, I think we should find a somewhat larger current to be collected at a somewhat higher speed.

The gross-ton-miles per ton of coal burned are given as 3.1, which is in line with the information we have.

Reference is made to 44 miles per day, average for 365 days, as being a high figure for Mallet locomotives. Some records of Mallets in mountain service averaged over periods of one year or more show a minimum of 48 miles, and a maximum of 75 miles, per day, and I do not think 44 miles is an exceedingly high figure, particularly as the higher figure includes for each locomotive at least one month out of service for general overhauling.

In connection with the 96-mile electrification of a mountain grade, I think too many electric locomotives are assumed; that is, 48 double-unit engines, when the maximum number of trains on the line is 28, as shown in the foot-note, page 1176.

The paper states that on a basis of 8 lb. per ton train friction, and a grade of 2.2 per cent, the drawbar pull is found to be 94,000. This is, then, arbitrarily increased 36 per cent to allow for bad weather conditions. Of course, the effect of grade is the same in all kinds of weather, therefore, the result of making this increase of 36 per cent in drawbar pull is that the friction is run up to 26.7 lb. per ton, which is very high, even for bad weather. If we use these figures, we find that the engine, with 128,000 lb. drawbar pull, for 1800 tons trailing in bad weather, will handle 2560 tons trailing load in good weather. Thus, the tonnage rating for bad weather is only 70 per cent of the good weather rating. This difference is much greater than that in common use on steam railroads.

Another indication that the total number of electric locomotives is very high is that the average works out only 75 locomotive-miles per day, per electric engine.

The paper gives some indications of the permanent investment to which Mr. Armstrong referred. Taking the cost of overhead and substations, and assuming the substations are on a basis of 200 per cent overload for short periods, it works out to $37.00 per kw. for substations and an overhead feeder system of 2,000,000 circular mils of copper in addition to the trolley. These figures seem high for permanent investment; for that reason I do not think 2400 volts d-c. is most suitable for heavy traffic. As it stands, 2400 volts is not sufficiently high; it may be fit for certain traffic, but for heavy traffic it is certainly too low.

Referring again to the matter of train resistance, we read that in descending "the power required for propulsion will be negligible for most of the descent, nevertheless, steam must be maintained in the boilers, and also, owing to the high frictional resistance of the Mallet engines, power will be required for all grades materially lower than the average value of 1.5 per cent." If we work this out for a 250-ton Mallet engine, with trailing load of 600 tons pushing it down hill, we obtain a result which looks rather high; that is, 80 lb. per ton frictional resistance for the Mallet.

The comparison is made on the basis of different amounts of

traffic for steam and electric operation. I think it should have been worked out to handle the same traffic, in which case the electric locomotive would have made a better showing.

Referring to page 1187, I ask if "the correct basis for estimating the commercial results to accrue from the electrical operation is to compare all those items which are affected by the use of electricity instead of steam," why is it that this is "inconsistent with the retention of the forms which have become customary in analyzing the results of steam operation"? It seems to me that is really the good way to get at the answer, rather than the inconsistent way.

In connection with Mr. Armstrong's remarks as to increase in traffic not materially affecting substation or feeder cost, I would like to call attention to some installations made in the past, where the substation and feeder costs have been materially increased when the traffic was increased. The Pittsburgh, Harmony, Butler & New Castle Railway, at 1200 volts d-c., was one case. Another was the 600-volt d-c. electrification of the West Jersey & Seashore Railroad.

George Hill: I have been impressed while sitting here listening to these two papers and the discussion of them, and from my own acquaintance with the trend of railway electrification, with the fact that railway men throughout the country are taking a greater and greater interest all the time in the electrification of steam roads.

In these days of ever-increasing effort toward high efficiency, and the desire to get the best and most out of everything that is done, it is gratifying to the electrical engineer to see the steam railroads turning more and more to the use of electrical power. It is especially gratifying to see that this is being done largely in a consistent and logical manner. That is, the roads which are adopting electrification, especially in connection with the handling of freight, are doing it by applying the electrification remedy to those points where it is most needed; I refer particularly to heavy grade work. I may mention at this time an example of this in the electrification of the Norfolk & Western Railway, the mountain grade division called the Elk Horn grade, between Bluefields and Vivian, in West Virginia. It is generally known that this electrification is in progress, and it is one of the cases where it has been found that a very material saving and a very satisfactory return on the investment will be effected by electrification. Our firm has had occasion to investigate and report on a number of electrification propositions of this general character, and it is evident that for many cases of this heavy mountain-grade character, electrification will make a very satisfactory showing, not only in the savings under equal conditions, but also by greatly increasing the capacity by increasing the speed and improving the reliability of the service, and thus the earning power of the property.

W. S. Murray: I realize that it is necessary for me to cut my remarks short, and this has been made possible by most of the wind having been taken out of my sails by the very excellent line of inquiries which have been asked by Mr. Wynne with regard to Mr. Hobart's paper.

I was very curious indeed about some of the statements in that paper, and doubtless the answers to Mr. Wynne's questions will bring the information I most desire.

There is one thing I want to try to emphasize that has struck me forcibly in the matter of electrification, and that is this: Electricity is nothing more than an agent to do the same work that steam has been doing for about 80 years, and in settling these problems of electrification, both with reference to level and grade conditions, it seems to me the first thing we electrical engineers owe to our railroads in this country before we begin to electrify them is to see if they have been reduced to the best steam basis.

1. We have been prone to base our opinions and our conclusions on electrical figures that have not got for themselves the same basis that steam has. Therefore, to repeat, we must get the territory to be considered upon a proper steam basis before we take up the matter of its electrification. Now, as the railroads have grown in age, so have the efficiencies gone down. Certain local conditions and matters that appertained to the relation of traffic and equipment schedule have not been caught up as they should have been; and so when we electrical engineers go into them, we set up first our wonderful schedules, and show the electrical economies above steam, and capitalize the project on a basis that takes care of the construction bonds, indicating a magnificent dividend on the electrical investment. Now, that has been the tendency and I think that we should be extremely careful to avoid such practises.

Now I want to draw attention to the fact that a steam locomotive can, if the fireman's arm holds out, develop its maximum tractive effort continuously. That is a very important point.

2. An electrical engine has no fireman's arm between it and its tractive effort, but it has in its place a temperature rise which must be reckoned with.

3. The electrical engine has the advantage of the steam engine for sustained horse power; but the steam engine has the advantage of the electrical for sustained tractive effort, *ex* fireman's arm.

It is within the realm of possibility that steam locomotives are to be of a different order in the future from what they have been in the past. Oil burning and automatic stoker locomotives will make us electrical engineers hustle to prove our case.

The electrical engineer who has a clear-cut understanding of the foregoing facts, knows their value, and so I can only draw your attention to Mr. Wynne's figures. He shows an interesting

line of ratios in regard to steam and electrical engines on different orders of grades. The most important part of Mr. Wynne's diagram is not shown, and that is the length of grade involved. These papers which we have been much interested in tonight are of an academic order; the real physical conditions of the problem are not sufficiently discussed.

There are many figures which Mr. Kahler has brought out which are most interesting and absolutely true; and yet the real question is their proper correlation and application to the specific problem in mind.

I want to extend a warm hand of friendship to my friend, Mr. Armstrong, who has joined me on the single-phase bandwagon.

The power houses of the single-phase and direct-current systems are about a stand-off. The direct-current locomotives cost less than single-phase locomotives, but the distribution system for the single-phase system is by far the more economical of the two. Now you see this interesting combination where we secure a minimum cost of power station, minimum cost of distribution and finally the minimum cost of locomotive. Mr. Armstrong has indeed built a beautiful bridge, over which I am very glad to walk and meet him half-way. As I have always had to admit that the cost of single-phase locomotives was more than that of direct-current locomotives, since from the time they have been manufactured they have necessarily been heavier, I have been as forcefully required to admit that the distribution system for the single-phase system possessed such inherent characteristics of economy as to far offset the greater cost of the a-c. locomotive, and if single-phase current for heavy trunk line traffic has now been accepted as the economic form for electric train propulsion my position would be truly illogical not to welcome with Mr. Armstrong the coming of the rectifier locomotive, which will bring out still more its economic characteristics. In the absence of the rectifier the single-phase motor was a necessity to make use of the economical single-phase distribution. In the last analysis of the true economics of any heavy trunk line electrification project it will be found that the single-phase motor rules out its direct-current brother. The direct-current motor has put up a good but a losing fight for its position in this field, and through the medium of the rectifier let us hope that it regains its former position. I am interested in the type of motor only so far as the position it may take in the consideration of the electrification as a whole. The fact that the direct-current motor may replace the single-phase motor through the medium of the rectifier, but stamps the electrification all the more as being single-phase, for the reason that the distribution system has made that end possible.

A. H. Babcock (by letter): The two papers by Hobart and Kahler dealing with trunk line electrification merely serve to emphasize a conviction that has been growing steadily in my mind for some years, that generalization with reference to

trunk line electrification is extremely dangerous. In hypothetical cases, or even in cases where only a preliminary estimate is required, often curious results are reached by the use of improper bases on which to form the arguments leading to conclusions. The incorrect premises may be due to a partial study of the case involved, or a desire to make a very favorable showing in order that capital may be interested to investigate farther, or to a variety of causes, but the result is the same; while in the hypothetical case, from a given set of assumptions one may argue himself into almost any desired position, in practise the hard and unyielding physical facts are met.

During the last ten years my office has made reports on every mountain railway exit from the Central California valleys, and on other mountain districts in other parts of the West Coast country. Often these reports have been the result of agitation on the part of power companies with a surplus of power for sale. In other cases they have been the results of pressure exerted by the manufacturers on the executives of the railway companies. In not a single one of the reports that have been made in considerable number, as stated, could it be said "that the operating economies which have been effected by superseding, with electric locomotives, the steam locomotives on such railways, are enormous and are indeed of such amounts as to defray in a very few years the initial outlays for substations, for feeders and contact-conductors, and for electric locomotives" (Hobart). Quite the converse is the fact and in every case on which a report has been made the conclusions have been adverse to electrification on precisely the reverse of the facts in the quotation above cited.

Whenever the request for such reports has been started by a power company, statements relative to "the very low cost at which the large hydroelectric supply companies in the West can profitably sell electricity" (Hobart), have been made by officials of the power companies; but it is a significant fact that when the same power companies have been confronted with the physical facts of the railway company's requirements as to quantity of energy, maximum demands for power, and load factor, invariably the rates quoted have been quite prohibitive, notwithstanding the fact that usually they are lower than those assumed by the authors of these papers, (Hobart, page 1180 and Kahler, page 1222). As a matter of fact, with fuel oil on the West Coast at ordinary market rates, say 70 to 80 cents a barrel, an energy rate greater than 5 mills is utterly prohibitive, as far as water power purchase is concerned; moreover, the annual load factor, although it "should not get lower than 60 per cent," (Kahler, page 1222), seldom rises above 20 per cent as a matter of fact, and as a rule the total energy charge can be wiped out of the annual statement without making a material difference in the conclusions, so small a part does it play in the annual operating cost when the fixed charges and other elements of operating expense are taken properly into account.

Not one of the projects that have come under my notice conforms in the slightest to the following—"But when it is understood that these Western hydroelectric companies already have enormous loads connected to their systems, it will be seen that the fluctuations of a couple of thousand kilowatts, more or less, imposed by the intermittent operation of a few freight trains, is not a factor of consequence" (Hobart, page 1162). Our freight trains require from 4000 to 4500 kilowatts apiece and thus far no power company on the West Coast, however large its service may be, has yet been found to view with equanimity the possibilities of a number of such loads being thrown instantly on or off its systems; furthermore, the above power demands are of such duration that the figures given represent the continuous capacity of locomotives per train.

The fact that so many men engaged in the study of these problems discuss them from the standpoints of the authors of the two papers from which quotations have been taken, indicates, of course, that in other parts of the country the extremely severe conditions of the West Coast mountain railroading do not obtain. It is obvious also that were I, whose experience in such estimating has been confined exclusively to West Coast work, to attempt to generalize from that experience and the information gained in the study of these projects, the result, if expressed publicly, might be, to say the least, embarrassing to me and amusing to some of the eminent gentlemen who have favored the Institute with general discussions in the past. Precisely this difficulty has been met with in discussing West Coast problems personally with Eastern factory engineers, and it was not until these same engineers came West and investigated on the ground for themselves that a mutual understanding of each others' words was reached. With this thought in mind the foregoing remarks are submitted, not at all in criticism of the papers referred to, but as supplementary thereto.

H. Y. Hall and G. W. Welsh (by letter): Mr. Kahler's paper states that only ten electric locomotives would be needed for the through passenger trains; this on a 468-mile line with three engine districts and three through passenger trains each way per day. Assuming that it is the intention to operate the 468-mile line electrically with three engine districts, as indicated by the paper, an examination of the train sheet shown in Fig. 2, for the through passenger trains, shows that there are actually required for the operation of three through trains each way per day, three locomotives on engine district No. 1, four on district No. 2, and three on district No. 3, or a total of ten locomotives actually required, assuming all trains to be on time and no extra trains. This does not include any locomotives "in shops, spares, in engine house, running to and from trains, and in helper service." The time saved in taking water mentioned is small for passenger service and for the above train sheet will not reduce the number of electric locomotives required for actual

service. On most western railroads during the heavy tourist season, it is practically an every-day occurrence to run passenger trains in sections; and on days of extremely heavy tourist travel, the number of trains is often increased by 40 to 50 per cent. Judging by the figures given in Table VI, it is evident that Mr. Kahler does not consider that more than one section of any train will ever be necessary. In this respect the road considered by the author is unique, since it is the only road in the western part of the United States which can run without extra trains. It would seem that an allowance of twenty passenger locomotives, instead of ten, would not be excessive on both the grounds of reliability and actual traffic.

Referring again to Table VI, under "Freight Trains," the ratio of maximum day to average day appears to be exceedingly low. On some of the through lines in California, it is not unusual during the heavy fruit shipping season to have a maximum day of 2 to 2½ times the average day throughout the year. Evidently, the number of locomotives must be sufficient to take care of the maximum day. In steam operation, on a large system, the usual way of taking care of this excess traffic is to rush all available locomotives from other parts of the system to help out the congested district. This is not possible with electric operation unless the entire system is operated electrically. Another point is that freight trains very seldom run on time and although they may be dispatched at stated intervals from one terminal, they rarely reach the other terminal with the same time interval between them. Therefore with the forty-three freight locomotives (that is, electric freight locomotives,) shown in Table X, we think the road under consideration by Mr. Kahler would find itself frequently with its cars at one end of the line and its locomotives at the other. Of course, in times of emergency, electric locomotives can be run over more than one engine district without injury, but in our opinion the actual requirements of the road under consideration would be more nearly realized if the number of freight locomotives given in the paper were increased by 50 per cent, or say to 60 locomotives.

It should be noted that under "Locomotive Repairs," the cost per locomotive mile given for single-phase locomotives is based on the published reports of two roads operating direct-current apparatus. It would be interesting to know what is the repair cost per mile on single-phase locomotives, but only one road in the United States operates a sufficient number of these equipments to give reliable information, and to the best of our knowledge this has never been published.

The "Estimated Cost of Electrification" given is altogether too low to be conservative.

It is not possible, for $5000 per mile, to build a double-circuit steel tower transmission line of sufficient factor of safety and with sufficient copper to hold the losses and regulation within the proper limits, especially with low power factor lagging current

as would obtain with a single-phase electrification. This cost should be increased to $6000 per mile.

Judging from the extremely low cost given, the author is not considering the use of catenary construction. For the class of service required, the catenary construction would be none too good. At a Pacific Coast point, located close to the source of supply of good and cheap cedar poles, it costs $2175 per mile (not including engineering and contingency) for single-track bracket, 1500-volt, d-c. catenary construction. In this case $2500 per mile should be used, on account of higher voltage, generally stronger type of construction for main line operation and to cover installation of feeder.

The double-track span construction would cost $4000 instead of $2600 per mile.

The four- or more track bridge construction would cost nearer $15,000 than $9000 per mile.

With the increase in first costs and increase in number of locomotives as given above, the total first costs would be $12,698,209 instead of $9,972,000, while the net estimate would be $10,686,209, instead of $7,960,000.

The total of maintenance of overhead structures and substations, Table XV, is too low to cover necessary emergency gangs, repair gangs, patrolmen, material, etc., for the proper maintenance of a 468-mile section of a single-track main line with so dense a traffic. This item should be increased at least 60 per cent.

Referring to Table XVI, Mr. Kahler has based his depreciations upon estimated first costs, excluding engineering and contingency. If in making estimates for immediate work it is necessary or desirable to add a contingency to cover fluctuations of material costs and unforseen items or difficulties, it is certainly necessary to add a contingency for work to be done 20 or 30 years after the making of an estimate. It is common knowledge that to do certain classes of work, it now costs three times as much as it did 20 years ago. Then again, it would not be desirable to do the work in the same manner twenty years hence, so it will be necessary again to pay for engineering. Including the engineering and contingency would increase the depreciation 15.5 per cent. A life of 15 years on poles and fixtures (item 18), would be nearer the accepted value than 20 years, as given, so the depreciation should be 6⅔ per cent instead of 5 per cent. With the increased first costs, the inclusion of engineering and contingency and increase in depreciation rate on "poles and fixtures," the total depreciation of overhead structures and substations would be $226,046 instead of $144,084.

The total of depreciation of electric equipment, Table XVIII, with increased number of locomotives, as noted above, and with engineering and contingency included in the cost upon depreciation, would be $107,115, instead of $64,740.

With the increases given above, the total cost of electric

operation (Table XX) would be $3,090,178 instead of $2,908,409 and the annual saving would become $758,231 instead of $940,000. This would give a net return of 6.8 per cent, which with interest of 5 per cent, would give a net profit of 1.8 per cent on the investment, which is too small a profit upon which to base a recommendation for electrification, as this estimated profit would be entirely wiped out if the "actual" expenses of electric operation were 7 per cent higher than the estimated operating expenses.

Mr. Hobart gives a first cost of $8,500 per mile for overhead contact line, rail bonding and feeder copper. Several paragraphs above he gives the annual efficiency, locomotives to substation, as 93 per cent. This would give an efficiency of 91.1 per cent during the heavy traffic period. With a substation spacing of 26 miles and 90-lb. rail, single track, the cost of the positive feeder alone (excluding trolley), to give efficiency of 90 per cent on maximum day, would be $6600. This is based on the use of aluminum at 33 cents per lb. erected, which is equivalent to copper at 15½ cents per lb. erected. This calculation is based upon a minimum condition of only one train at a time between substations, whereas with the speed of trains and interval of starting given, it is possible to have two trains at a time on the up-grade between substations. In our opinion, to obtain an annual efficiency of 93 per cent, it would be necessary to spend at least $12,000 per mile for overhead contact line (catenary construction), rail bonding and aluminum feeder. It should be borne in mind that on mountain divisions, it is necessary to blast at least 60 per cent of the holes for setting trolley poles.

During the maximum traffic period of 18 1800-ton trains each way per day as given, with 12,200 kw-hr. per locomotive journey and the same percentages added as shown on page 1180, the average load per substation will be 6150 kw. instead of 3200 kw. as given. With a load factor of 25 per cent, the maximum load would be 24,600 kw., but with an average of 6150 kw. the load factor would probably be as good as 35 per cent, which gives a maximum of 17,600 kw. per substation.

With an average load of 6150 kw. the heating load per substation would be not less than 8200 kw., which would require 8000 kw. for regular service and 2000 kw. for spare, making a total installed capacity of 10,000 kw. per substation, which at $30 per kw. would amount to $300,000 per substation instead of $160,000, as given, or as a total for the four substations, $1,200,000 instead of $640,000 as given.

With the above changes, the cost of overhead construction, bonding and substations would be:

96 miles overhead and bonds at $12,000	$1,152,000.
Sidings, same as given by Mr. Hobart	84,000.
Substations	1,200,000.
Total	$2,436,000.

On the basis of 16 per cent of first cost as given by Mr. Hobart, the fixed charges, maintenance and operation of substation (not including electric energy), would amount to $389,760 instead of $246,000 as given.

Note 17 states that, "It is desired to err on the side of favoring the steam locomotive whenever there is room for divergence of opinion." In view of this statement, it is not quite clear why he has used the 250-ton Mallet locomotive in handling the 600-ton train, or three of these locomotives for an 1800-ton train, when there is in actual service today a 300-ton Mallet locomotive which will haul a 900-ton trailing train on an average grade of 1½ per cent at average speeds in excess of the 12 miles per hour assumed in this paper. Naturally, if fewer locomotives of a larger rating are used, the operating costs, such as fuel consumption, locomotive repairs, enginemen's wages, etc., will be materially reduced.

Also, the cost of 250-ton Mallets is given as $45,000. The 300-ton Mallet mentioned above costs new approximately $33,500, and the heaviest Mallet locomotives ever built (weighing 425 tons) cost slightly less than $44,000. It is evident that the figure of $45,000 is much too high.

The foregoing analysis of Mr. Hobart's paper, (also of Mr. Kahler's paper), is based on West Coast operating conditions, as developed in the study of some of the most important heavy trunk lines operating over the Sierras. It shows that while he has made a favorable showing for the very general case he has assumed, his results, if applied to any of the concrete cases known to the office with which we are connected, would be disappointing to those who might be induced thereby to invest money, and who expect profit. Based on our experience, his estimated costs for overhead construction and substation equipment are very much too low; hence his electric operating costs are correspondingly low; he has considered steam locomotives only two-thirds as powerful as those now in service on our lines, and in his estimate of first cost, he has taken these comparatively small steam locomotives at a unit cost essentially the same as was paid for the largest steam locomotive ever built for West Coast work. His estimated first costs for steam locomotives are at least 30 per cent higher than West Coast practise shows to be reasonable, and his estimated steam operating costs are correspondingly high. In general, then, according to our experience, the costs of steam operation have been magnified and the costs of electric operation minimized, in this, as in many other such very general solutions of a very complex problem.

F. W. Carter (by letter): The subject matter of the present papers is of great importance and discussion cannot fail to furnish valuable information. I think such papers as these are best written with a view of instructing or convincing the railway engineer rather than the electrical engineer, and the greatest care should accordingly be taken to avoid an undue bias in favor

of electrical working. But from the nature of the case, in which comparison is made between an established system and a newer rival, the figures for the established system are likely to be based on actual operation, and to cover a number of more or less trivial or accidental circumstances which are apt to be overlooked in making the comparison; I think there are signs of this tendency in both the present papers. For instance, in Mr. Hobart's express passenger proposition he adopts the figure of nine lb. per ton average train resistance; this is a reasonable figure, considering that the mean train resistance is necessarily greater than the train resistance at the mean speed, and moreover that the figure includes the effects of curves, adverse weather, and other difficulties of the route. He, however, deduces his coal consumption directly from the work done against train resistance, suggesting an equipment efficiency of the order of 87 per cent. But the energy dissipated in final braking is of the order of 75 h.p-hr., and although townships are more sparsely scattered in the United States than in England, it is doubtful whether a typical 100-mile run should have been assumed without some speed restrictions, each consuming, say, 60 or 70 h.p-hr., while a signal stop is not likely to be an infrequent occurrence. Altogether, I think that to accord with actual operation, the coal consumption in the electrical case would have been better assumed 15 or 20 per cent greater than Mr. Hobart finds it to be. In the steam case I surmise that the corresponding figure is derived ultimately from the integral consumption in actual service, and therefore includes the effects of all the normal circumstances of such runs.

Mr. Kahler, again, seems to me, however, to have made his calculations without due regard to limitations that the traffic department may impose. He shows that it is possible to handle a certain tonnage of freight with but few more than half the number of locomotives in service than would be required under steam operation. This is certainly an engineering possibility, but if it is a commercial possibility, it is a pretty sure sign that the line is congested, and the proposition takes on an entirely new aspect on this account. Mr. Kahler assumes the average weight of train as 80 per cent of the maximum. Under English conditions, I believe this figure is nearer 60 per cent, but however this may be, the effect of increasing the capacity of the locomotive would in general be to reduce the figure by, say, 10 or 15 per cent. Many light trains would go forward at the instance of the traffic department without reference to the ultimate capacity of the locomotive. The number of freight locomotives required in actual service at any time would, I think, be nearly as great with electric operation as with steam.

Comparing Tables IX and XIII, I am inclined to think also that the number of electric passenger locomotives required is somewhat underestimated, for the exigencies of traffic would

keep locomotives waiting in service, much as it does under steam operation. It would seem that in the case of the Butte, Anaconda and Pacific electrification, 23 steam locomotives are replaced by 17 electric, no such reduction as Mr. Kahler finds possible.

I note that Mr. Kahler has assumed the single-phase system of operation, but he seems to have based his estimate of locomotive repair cost on results obtained with continuous-current locomotives. Since the repair of the single-phase electrical equipment has been found to cost something like three times as much as for the corresponding continuous-current equipment, I am disposed to think his figures here a little too low, and I also think the number of his laid-up locomotives is on the low side for the same reason. His energy consumptions, too, appear to me somewhat low for normal operation, which Fig. 3 shows to have been contemplated, the frequent stops and intervals of running with brakes applied resulting in the dissipation of much energy. Although my contribution to the discussion is generally of the nature of criticism, I should like to express my appreciation of these very able and suggestive papers.

F. C. Merriell (by letter): The financial showing which has been so conservatively developed in these discussions finds very little consideration from railway operating officials, because of two fancied weaknesses which are believed to attend electric traction.

Frequent failure of electric locomotives in heavy traction service is believed by steam railway men to be inherent in a device, which to them, appears to be more complicated and less substantial than the steam locomotive, and even the most elaborate and painstaking analysis of the economies of electrification will not avail against this belief, unless the operating experience of present electrifications shall prove that analysis to have been very conservative. The fact that partial failure, of a steam locomotive is but little better than total failure while partial failure in an electric locomotive will usually not prevent it from getting in the clear, and perhaps making some progress until help can reach it, will have to be strongly urged even after the railway man has been convinced that of the two devices the electric is the simpler and the more substantial.

As appears in these discussions, the first divisions to be electrified will be those where heavy mountain work occurs and pusher service is required, and as these places are nearly always at high altitudes and subject to severe weather, steam railway men now believe that electric traction will, in such locations, meet obstacles which it cannot withstand. They admit the inefficiency of the steam locomotive to cope with extreme cold weather by their customary reductions in train tonnage as temperatures fall, which follows quite as much from the fact that the engines cannot make steam as from the poor conditions for traction. The electric traction man, on the other hand, expects his

motors to operate at greater loads during cold weather and is thus enabled to push his train tonnage up to the limit imposed by the condition of the track. Experience of heavy traction lines and such electrifications as are now in operation shows that distribution systems can be maintained without undue expense against the coldest and worst weather and will thus, contrary to the prevailing notion, cause less interference with traffic than engines which will not steam. The analysis of traffic movement on western roads will usually show that a part at least of the greatest congestions tends to lap over into extreme cold weather, as for instance the business of roads handling both deciduous and citrus fruits, which business will require much tonnage in deciduous fruit to be moved at the beginning of winter, while tonnage in citrus fruits will become quite large before it ends, all of which should tend to make the advantage of electric traction appeal more strongly, as soon as the electrical fraternity is able to assure the railway operator that he can rely upon electrical machines for continuous service and few failures.

The stimulation to local main line traffic which is mentioned as possible with electrification can also profitably be extended to feeder lines, and many of these which now operate at a loss might be brought nearer to a paying basis than they now are. It is the contention of railway officials that feeders as separate entities rarely make a profit (being principally valuable for the traffic they bring to the parent system), but the same standards of service, convenience, and efficiency, which the flexibility and economy of electric traction effect upon main line traffic, will without doubt render feeder lines more justifiable than they are considered at present.

H. F. Parshall (by letter): With reference to the two papers by Mr. Hobart and Mr. Kahler, I may say, speaking generally, that both papers would have been more convincing to railway engineers if accompanied by figures showing representative results obtained in good steam practise. According to my own experience and observations, both have assumed better results than are being obtained or are likely to be obtained in steam locomotive practise. The paper by Mr. Insull gave results obtained on several roads which led to the conclusion that the cost by steam locomotion is much higher than is commonly assumed. Personally, I think the time has passed when the electrical engineer need adopt the position of apologist to the steam engineer.

The electric locomotive is *ab initio* the cheaper machine to operate. The real problem is to determine at what point the density of traffic is sufficient to justify the electrical installation. The fixed element is the conducting system between the locomotive and the power system. The cost of fuel of the electrical system under ordinary conditions is not more than half that with the steam system, but, on the other hand, the cost of the steam locomotive installation is not often more than 20 to 25 per cent

of the cost of the electric locomotive installation including the conducting system.

Under favorable conditions the cost of maintenance of the two systems is not very different. Under some conditions, however, the cost of maintaining the steam locomotive system must be materially greater. With cheap hydroelectric power and expensive coal, the electric system pays for itself with moderate traffic density. With increasing labor difficulties and increasing cost of fuel, the case of the electrical system becomes every day stronger, as less men, less skilled mechanics and less fuel are required with the electrical system.

From a strictly operative point of view, my own experience is limited to my activities as Chairman of the Central London Railway. I had designed the system, including the power station, and had advised in its operation for some years, but after becoming Chairman, I had to see through two strikes, one a general railway strike and the other a general colliery strike. During the general railway strike, the power station, as the heart of the railway, was a special cause of anxiety. In the coal strike, every department of the railway was crippled. To keep the power station supply assured, special efforts, in addition to the usual ones, had to be made. While I have been largely associated with electric power installations, I came to the conclusion that railway managers had enough to do without embarking on that class of business. Further, that the central power undertaking is in a better position to guarantee a supply under all conditions than any railway company can hope to be, and also, owing to the diversity conditions, can supply cheaper. With the question of supply settled, the electrical system of traction is in a stronger operative position than the steam system.

As to the type of locomotive for heavy freight work, with moderate facilities for repair, I should prefer the side-bar type with motors individually replaceable. The maintenance of such a locomotive is small and the time to carry out repairs a minimum. Axle-driven types of either locomotives or motor cars require a higher degree of skill in maintenance and operation.

With reference to the voltage of the overhead conductor system, owing to the small cost of the conductors as compared with the supporting structure there appears small advantage in exceeding 2500 volts. The size of overhead conductor is largely determined by the maximum current required by the individual trains, so that with increasing traffic density the growth is met by increasing the number of substations without reducing the efficiency. In the case of a line 400 miles in length I made a careful study as between 5000 and 2500 volts d-c. overhead conductor pressure, and came to the conclusion that the saving by the higher voltage was too small to affect the general result. In the case of the 2500-volt installation, the motors could be safely worked at full line voltage, which in my judgment is a material advantage in heavy railway working.

I am glad to see evidence in these two papers that a truly commercial spirit is coming into effect in considering railway problems.

Charles P. Kahler: The foregoing discussion was very interesting to me, in that, although some speakers confined their remarks to the narrow limits of systems of electrification, types of locomotives, and other details, the comparative economics of steam and electric railroad operation, which is really the most important part of the problem, received considerable attention. The data and other information given in my paper, *Trunk Line Electrification* furnished a comparison between steam and electric railroad operation, and the paper could hardly be classed as advocating any one system of electrification, although Mr. Armstrong seems to think it does.

Mr. Armstrong states that the electrification costs depend principally upon the locomotives, substations, and trolley and feeder copper, and that the locomotive costs are high in the case of the single-phase system, while the substation and trolley and feeder wire costs are high in the case of the direct-current system. This is approximately true, considering the single-phase commutator motor locomotive alone, but the locomotive cost would not necessarily be so materially different from the direct-current system if the split-phase locomotive, or the mercury vapor rectifier locomotive to which he refers, were used.

Mr. Armstrong assumes that the substation and trolley and feeder copper costs remain constant as the traffic increases, while the locomotive costs increase as the traffic increases, and draws the conclusion that, even though the single-phase system proves most economical with moderate traffic, as far as first cost is concerned, the direct-current system will, when considered with a 50 per cent or 100 per cent traffic increase, be most economical. Mr. Wynne mentioned two electrically operated railroads where the substation and copper line costs have been materially increased by an increase in traffic, which shows the incorrectness of Mr. Armstrong's premises, and as a consequence, makes his conclusions wrong.

Very few railroad improvements involving any large sums are made without a thorough investigation by the railroad officials of the effect of increasing the traffic. Practically none of the important line or grade changes with which I have been connected were made without considering the effect of at least doubling the traffic. In our investigations of steam railroad electrification, we have gone still further, and besides considering the effect of a change in the volume of traffic have also considered the effect of electrification upon the whole railroad, rather than confining our studies to isolated sections. As a result of numerous studies of this character, I am inclined to believe that electrical engineers, who are usually unacquainted with actual steam railroad operating conditions, would be very much slower in advocating thier own particular fancies if their effect on the whole system was first considered.

The substation and feeder copper cost for a direct-current system which would be of sufficient capacity to permit the operating of trains under such close headway as would be possible on a steam-operated railroad during a congestion or other emergency, would usually be so great as to make electrification unwarranted for many years. As is generally known, the electric distribution system of a direct-current line is not generally designed for any possible emergency, but an allowance is only made for a reasonable contingency, which often is determined by electrical men not familiar with steam railroad operation. On the other hand, it would be commercially possible with a high-voltage trolley, such as is used on single-phase systems, to provide a distribution system which could expeditiously handle almost any congestion or emergency which a steam-operated railroad could.

The development of the mercury arc rectifier locomotive, of which Mr. Armstrong speaks, will no doubt be welcomed by all interested in heavy electric traction work, since direct-current locomotives—which are preferred by Mr. Armstrong and other advocates—can, through the mercury arc rectifier, be made to operate by current from a single-phase trolley. If this new locomotive serves no other purpose than the settlement of the system question, it will have done good service.

The introduction of the mercury vapor rectifier locomotive, together with the split-phase locomotive, which can also be operated from a single-phase trolley, would indicate that the single-phase system, besides providing low cost substations and low cost distribution system, has a further advantage in being adaptable to four or five different types of locomotives.

Mr. Babcock's remarks about inaccurate conclusions being liable to result from generalizing are hardly in accord with his criticism of load factor. He compares his estimated load factor for the proposed electrification of the Southern Pacific lines over the mountain ranges surrounding the Central California valley—which are short in length and where the average grades are heavy—with a long line of railroad with light average grades. It would require about a day and a half for freight trains to cover the 468 miles of line and the stopping or starting of a train at either end of the line would not make a large increase or decrease in the total load, as there would be so many more trains in simultaneous operation on the line, which would not be the case with the shorter line where only a few hours were required to make the run. In fact, the daily load factor would be very high for the longer line.

The California lines have to contend with the heavy freight traffic during the fruit season, whereas on the 468-mile line discussed in my paper the peak of the west-bound business, of which coal forms a considerable portion, does not happen at the same season as the peak of the east-bound traffic, of which lumber forms a large proportion. Also, the maximum passenger traffic

does not occur at the same time as either the peak of the eastward or westward freight traffic. The above, I believe, shows why it is possible to get an annual load factor of 60 per cent for the 468-mile line and only 20 per cent for the short mountain lines to which Mr. Babcock refers.

I cannot check Mr. Babcock's statement that the purchase of electric power at a greater rate than 5 mills per kw-hr. would be utterly prohibited where oil is selling at from 70 cents to 80 cents per barrel. Three barrels of oil are equivalent to one ton of coal, allowing for the higher efficiency of the oil-burning power plant, which would be equivalent to coal at from $2.10 to $2.40 per ton. With a load factor of 20 per cent, the fuel cost alone would not be far below 5 mills per kw-hr., and when the fixed charges and the other operating expenses were added a rate of 5 mills would appear to me low, especially as nothing was allowed for freight on oil or additional charges for transmission lines in case the power plant is built near the oil fields.

Hydroelectric power is at present being sold at as low a rate as the above in many sections of the West. I quoted in my paper the rate of 5.36 mills per kw-hr. which the Great Falls Power Company has given the Chicago, Milwaukee & St. Paul R.R. Also in some sections of southern Idaho power for heating and irrigation pumping is obtained at even lower cost.

Mr. Carter doubts the practicability of making a reduction in the number of freight trains, for traffic reasons, even though the electric locomotives can haul heavier freight trains. Without going into any technical discussion, I would advise that a number of Mikado locomotives, whose tractive power is about 15 per cent greater than the consolidated locomotives, has lately been put in operation on one of the engine districts of the 468-mile line, and an actual reduction in the number of freight trains has resulted. Further, on another division, where conditions were somewhat similar, the train weights were increased by reducing the grades, resulting in a material reduction in the number of freight trains.

For English conditions, Mr. Carter gives the average freight train weights at 60 per cent of the maximum. The figure of 80 per cent given for the 468-mile line considered in my paper was not assumed but was an actual record. This has been increased to 86 per cent for the fiscal year ending June 30, 1913, being 91 per cent for west-bound trains and 82 per cent for east-bound trains.

The possibility of handling the given freight tonnage with only 43 electric freight locomotives has also been questioned, although Mr. Carter qualifies his remarks with the statement that if this can be done it is a pretty sure sign that the line is congested. While this is true, the congestion is partly caused by the equipment troubles on the two helper districts near terminal No. 2.

The train sheet in Fig. 3 was for the day of maximum traffic. Of the freight trains shown, only two are scheduled, the re-

mainder being run as extra. This maximum day train sheet shows that only six freight trains were in simultaneous operation on engine district No. 1, six on district No. 2 and seven on district No. 3, a total of 19 freight trains, requiring 19 freight road locomotives. Additional locomotives would, of course, have to be allowed to provide for helper locomotives, time in enginehouse, shops, etc., but it should be remembered that at the time of maximum demand there would generally be a minimum number of locomotives in the enginehouse. As stated in the paper, the number of electric freight locmotives required is based upon the number of steam locomotives actually used to handle the traffic, allowing for the reduction in the number of freight trains by electric operation and the fact that an electric locomotive is nearly always ready for service and needs to spend little time in the enginehouse. I judge my estimate of 43 electric freight locomotives not only to be large enough to handle the given tonnage but also to provide a larger margin than is usually allowed for steam service.

With regard to the number of electric passenger locomotives, it should be mentioned that of the the three through passenger trains each way per day shown, one is really a solid mail train. No extra mail trains are operated and the number of passenger trains operated in addition to the two through passenger trains scheduled is small, which will account for the apparent narrow margin allowed in the number of electric passenger locomotives. Further, it was proposed to make districts Nos. 1 and 2 one passenger run, there being no objection to this on account of grades or a 16-hour labor law, as would be the case with freight trains. This practise of making the passenger runs double the freight runs is now being followed on some districts with steam locomotives.

In the case of local passenger traffic, the volume is not so uniform as the through traffic, on account of state and county fairs and other things requiring excursion and extra trains, but 14 motor cars were allowed for this purpose. Most of these local extra trains are operated on the west end of the line and the extra cars allowed can be held in readiness at terminal No. 2.

Possibly Table VI, in regard to number of trains, as compiled, should have some explanation to make things clear. The figures shown under the maximum day column mean the total number of trains on the maximum day. The maximum day of passenger traffic does not happen at the same season of the year as maximum freight traffic, as stated, and although the 16 freight trains shown under the maximum day column of district No. 1 are the maximum number, the 10 passenger trains shown in the same column are not the maximum number of passenger trains operated but only the number operated on the maximum day for both passenger and freight traffic. The total number of trains per day, 26 as shown for district No. 1, is, of course, the maximum number for the year. The same applies to the other districts.

The number of passenger trains in the average day column is given in round numbers to simplify computations, the actual figures being 10.5 passenger trains for district No. 1; 8.2 trains for district No. 2 and 8.1 trains for district No. 3, the extra trains being principally local trains. Since the number of passenger trains was taken the same for both steam and electric operation, this would not materially affect the results, which would not be the case for freight service, and the exact freight train figures had to be used.

Although some direct-current locomotive repair costs were quoted in my paper, the electric locomotive repair costs used in the estimates were based upon a study of the comparative repair expenses of the different parts of steam and single-phase electric locomotives, as outlined on page 1217, which shows that it was estimated that a single-phase locomotive would cost about 45 per cent as much as a steam locomotive for repairs. For the direct-current locomotive costs quoted, this figure gets as low as 36.5 per cent, showing that an allowance was made for the relative cost of alternating-current and direct-current locomotives.

The foregoing answers most of the questions put by Messrs. Hall and Welsh. The estimated cost of the steel tower transmission line was based upon the actual cost of a steel tower line lately built parallel to the railroad, the material being distributed by work trains on the railroad, and, if anything, is high.

Catenary construction was, of course, proposed for the high-voltage trolley line. The figures quoted by Messrs. Hall and Welsh appear high even for California conditions, or else they include the cost of the copper trolley.

A number of Mr. Murray's remarks are worthy of careful consideration, especially as he does not underestimate the steam locomotive. He believes that in making comparisons between steam and electric operation of railroads some consideration should be given to the improvement of the steam service, and there is no question but that more consideration will be given to steam railroad electrification by both operating and financial railroad men if the matter is presented in this way. For instance, steam operation of the 468-mile line discussed in my paper could be improved by the use of Mikado locomotives for freight service instead of consolidated locomotives, and by revising both the ruling and helper grades. However, this would take very nearly as much money as required for electrification and the reduction in operating expenses would not, with the present traffic, pay the fixed charges on the investment, while by electric operation a fair return would be had on the investment.

The numerous advantages of substituting electric power for steam on mountain grades, mentioned by Mr. Hill and Mr. Merriell, are generally conceded even by many steam railroad men, and are in accord with investigations made of mountain grades on our lines. Mr. Babcock seems the only one unable to make any showing for electrification on mountain grades.

Our investigations would also indicate that many engine districts of only moderate grades could be more economically operated by electric power than by steam, and in some instances show up better than even the mountain sections; the reason being that on some moderate grade sections the number of freight trains can be very much reduced by electric operation on account of the characteristic of the electric locomotive to operate at overload for short periods. On mountain grade sections, however, the continuous rating of the motors is more important, and although some reduction can generally be made in the train service, it is not as great as can often be made on some moderate grade engine district where the ruling grades are short.

Roger T. Smith (by letter): Mr. Kahler's paper is interesting to English electrical engineers from the complete method of analysis adopted. The examples taken do not, however, invite criticism either of the constants or of the results, since they are not comparable with anything in the way of steam or electric traction that we have or are likely to have in England.

Mr. Hobart's paper, while of course taking its examples from American practise, deals largely with certain fundamental constants for both steam and electric traction common to all railways. The method of analysis used and its lucid presentation conceal the great amount of work which must have been done in the preparation of the paper, nevertheless certain of the constants used in the calculation can only be considered as a first approximation. It may be useful to compare some of them with similar figures taken from English experience, and through the kindness of Mr. G. J. Churchward, locomotive, carriage and wagon superintendent of the Great Western Railway, England, I am enabled to consider several of the constants used by Mr. Hobart in the light of English experience on the longest English railway. While confirming or criticising Mr. Hobart's constants, it is to be remembered that the English figures put forward are for conditions for the most part very different from those in America. Without Mr. Churchward's help no steam figures could have been given, but even these figures are also only to be looked upon as approximations, and Mr. Churchward must not in any way be held responsible for the manner in which the figures are presented.

Page.	Line.	Constant or Assumption.	Deduction affected by assumption.
A.	B.	C.	D.
1151.	29.	Coefficient of adhesion, 0.20.	Maximum available tractive effort.
1152.	6.	Average tractive effort over 100 miles for both loco. and load 9 lb. (10 lb.) per ton at average speed 50 mi. per hr.	The whole subsequent investigation depends on this figure.

Mr. Hobart deals first with steam and electric constants for a fast passenger service covering 100 miles in two hours.

Steam figures are given for a Pacific 4-6-2 type locomotive. The difference between the American ton and English ton may easily result in considerable confusion in comparing constants used in the two countries, and while my figures are all given in American tons of 2000 lb., the equivalent in English tons of 2240 lb. will be given enclosed in brackets. The author's engine weighs 115 tons (103) with 85 tons (76) adhesive weight, hauling a train of 750 tons (670). The comparative figures will for the most part represent results obtained with 4-6-0 type engines having a weight of 85 tons (76) with 62 tons (55½) adhesive weight, hauling passenger trains rarely exceeding half the weight of the American train.

The value of the coefficient of adhesion should not be taken as higher than 0.20. Experience with trains of about half the weight of the author's train gives 9 lb. train resistance per American ton (10 lb.) as a good average figure. Sufficient data are not available to determine whether the tractive effort is the same for the locomotive as for the coaches but it is to be remembered that this confirmation of the author's figures applies only to the coaches. There is reason to believe that train resistance is greater for the locomotive, and there is considerable advantage in dealing only with drawbar forces, such as can be measured on a dynamometer car, rather than with forces in the cylinder, the measurement of which by means of the indicator is extraordinarily difficult and liable to many errors.

A.	B.	C.	D.
1152.	9.	Efficiency from cylinder to crank pin, 85 per cent.	The average i.h.p. required throughout the journey, the coal burnt and the journey efficiency.

This efficiency would be more satisfactory if stated as between cylinders and rims of driving wheels. While curves of drawbar h.p. plotted with speed under specific conditions can be readily drawn to connect many points determined experimentally, the corresponding i.h.p. values are very hard to connect by a smooth curve. An average value of ratio $\frac{\text{drawbar h.p.}}{\text{i.h.p.}}$ may be taken to be 70 per cent, and the indicated h.p. under the author's conditions would on this assumption be 1290 instead of 1320, thus checking the value of 85 per cent very closely.

A.	B.	C.	D.
1152.	14.	Coal per i.h.p. = 3.5 lb. of calorific value of 14,000 B.t.u. per lb.	The coal burnt and the journey efficiencies from coal to cylinder and to wheel rims.

On trials where the ratio $\frac{\text{d-b. h. p.}}{\text{i. h. p.}}$ was 0.70 the pounds of Welsh coal of a calorific value of 15,400 B.t.u. per i.h.p. were 2.75, which would probably correspond to 3 lb. per i.h.p. for the author's lower calorific value. Taking the actual figure of 2.75 lb. for the better coal the journey efficiency from coal to drawbar is increased from 3.53 to 4.1 per cent.

A.	B.	C.	D.
1153.	17.	Coal used for firing up and at end of journey 3000 lb. or 32½ per cent of coal used on 100 mile run.	Affects the reduction of journey efficiency from coal to drawbar.

The figure 3000 lb. for the coal used for firing up and at end of journey would be considered very exceptional. About 800 lb. for firing up and 1100 lb. left in the firebox at the journey's end may be considered as representative figures for the largest English engines. This added to the coal used on the run would reduce the journey efficiency of coal to drawbar from 4.1 per cent to 3.2 per cent as compared with the author's figure of 2.85 per cent, the coal per drawbar h.p. amounting to 5.2 lb. instead of 6.86 lb.

For the electric locomotives, if we accept the author's assumption that the resistance per ton of locomotive is the same as for the coaches, and the other carefully prepared and fair chain of efficiencies between the coal bunkers and the rims of the drivers given on pages 1154 and 1156, the final figure for this efficiency given by the author is 6½ per cent. With the steam figures already given for an English railway with locomotive coal of 15,400 B.t.u. or 6 h.p-hr. per lb., 57 per cent of the coal used by the steam locomotives would be required to haul the train electrically, as compared with the author's 47 per cent.

If steam locomotive working costs include coal, water, running wages and superintendence, lubricants, small stores, and locomotive repairs and renewals, the average cost of working a locomotive—that is, the total of these costs divided by the total number of locomotives in service—is about $5000 per annum.

Of these costs, coal and water account for about one third. It is suggested that these total costs, averaged over the whole stock, and then modified to suit each type of locomotive for which the average consumption of coal per mile is known, would be the most useful figure for comparison between steam and electric locomotives. I regret not to be in a position to give this analysis for different types.

In comparing steam and electric locomotives for fast passenger service it must not be forgotten that, with increasing speed, the series motor falls off in output much more rapidly

than the steam cylinder. The type of English steam locomotive most in favor for fast passenger service can give a measured (not calculated) drawbar h.p. of 1100 at 70 miles per hour. The Pacific type could of course give a greater h.p. Have any electric locomotives in America given a measured drawbar pull of 5900 lb. at 70 miles per hour?

Agreeing with all that the author has said as to the purchase of electricity in preference to its generation by the railway, the British system of small municipal electric supplies in each town militates against the price of electricity offered by the large power companies falling to a sufficiently low figure except on the N. E. coast, where attractive prices are offered for traction. This has an important bearing in connection with the type of traffic dealt with in the second part of Mr. Hobart's paper under the head of "Mountain grade railways," where the hauling of heavy goods trains is considered firstly up 0.3 per cent grades and secondly up 1.5 per cent grades.

Here again our conditions are different. There are probably 700,000 privately owned traders' wagons in the United Kingdom for which the drawgear is, when new, tested to 56 tons (50). This permits of a maximum tractive effort of 13½ tons (12) and a maximum starting effort of 19 tons (17), and no locomotive giving more drawbar pull than this is required for general use. But apart from the loss of strength by wear, a considerable percentage of traders' wagons are much below this standard and in general make very heavy freight trains impossible. On some railways and in some classes of mineral traffic the company's own wagons are solely used and in such cases drawgear can be suited to heavier trains, but there is no difficulty in building, within the British load gage, steam locomotives (such for instance as those of the 2-8-0 Consolidation tank type with 70 tons (62½ tons) adhesive weight) capable of pulling the heaviest trains containing traders' wagons which from the strength of their drawgear it is safe to marshal. In this country, therefore, save in some special cases, the advantage of hauling heavier goods trains than can be hauled by a steam locomotive does not exist. In spite of this, the electric hauling of heavy goods trains in hilly districts is, after suburban passenger traffic, the most promising field for electric traction in this country, on account of increase in possible speed.

Let us turn again to the author's constants, remembering the British drawgear limitation in the possible maximum weight of goods trains in general.

A.	B.	C.	D.
1163.	19.	Total resistance of trailing load at 14 mi. per hr. = 4 lb. (4.5) per ton of loaded train, and 8 lb. (9) per ton of empty train, both at 14 mi. per hr.	The drawbar h.p. and all subsequent results.

Different load conditions in the two countries make comparisons difficult. For a 560-ton (500) train the resistance per American ton was 6 lb. (6.7) and for the empties weighing 215 tons (190) the resistance per American ton was 15.1 lb. (15.9), but the speed was 20 miles per hour instead of 14 miles. The value 560 tons, approaches the possible British limit of train weight with a ruling gradient of 1 per cent.

A.	B.	C.	D.
1164.	2.	Starting adhesion from 25 per cent to 30 per cent.	The maximum starting effort of locomotive.

The adhesion at starting with the 2-8-0 type of goods engine is 0.32.

No useful comparison can be made with English conditions, of the various constants leading to the efficiency for mountain grade locomotives between the coal and the drawbar. The amount of 30 per cent added for the coal used when the locomotive is standing can, however, be confirmed.

It is not possible to give a figure comparable with the author's figure for locomotive repairs. It is presumed that the figure of 10 cents per mile per 100 tons is an average figure and that for the Mallet locomotive under consideration it would be more.

Only one other figure used in the author's interesting comparisons between steam and electric locomotives on mountain grades can be given from experience this side, and that is with reference to the 16,000 traffic miles per annum of the Mallet locomotive. On a Welsh section including a ruling gradient for 2 miles of 2.0 per cent the average annual mileage of the 2-8-0 type of locomotive is 15,000.

It is a misfortune that the type of goods service in hilly districts for which ele ctric traction is most suited in England is conducted under such very different conditions from those obtaining in America that a comparison with the author's figures is only possible in one or two instances. Such comparisons as have been made point to the close agreement of the author's constants with those obtained from one English railway.

H. M. Hobart (by letter): The more valuable portions of the discussions of the papers by Mr. Kahler and myself consisted in written contributions containing a large amount of quantitative data which required detailed analysis in order to disclose its significance. Indeed, the significance of the contributions of Messrs. Babcock, Hall and Welsh have only become clearly apparent after studying them in conjunction with Mr. Babcock's paper entitled *Mountain Railway Electrification*, which is published in this volume of the TRANSACTIONS, page 1845. In this paper Mr. Babcock considers a mountain railway which in many respects is practically identical with the case which I worked out in my paper, and it is only recently that I have been able

to study all this material. This study has satisfied me that Mr. Babcock may be in error in extending his unfavorable conclusion as regards electrification of mountain railways to cases where the conditions are less favorable with respect to low cost of fuel, than in the exceptional case which he has considered. Mr. Babcock has based his steam locomotive costs on the use of oil purchased at about one cent per gallon or 42 cents per barrel. Oil fuel at such a price is equivalent to lignite (of a calorific value of 11,000 B.t.u. per pound) at a price of $1.60 per ton. For my example of a 96-mile mountain-grade railway I assumed a price of $2.40 per ton. This price is the lowest which could be considered representative. I devoted a page of my paper to pointing out and emphasizing the fact that with decreasing price of fuel the case for electrification rapidly became less favorable. The substitution of $1.60 per ton for fuel in place of my figure of $2.40 per ton would have greatly decreased the margin in favor of electrification.

It will be agreed that the price of about one cent per gallon (42 cents per barrel) for oil fuel is local in its application. At a price of 2 cents per gallon (84 cents per barrel) the item of $241,000 for locomotive fuel in Mr. Babcock's paper becomes $482,000 and increases his "Steam" total of $687,000 to $928,000. Furthermore, Mr. Babcock gives items for first cost of (I) Substations and (II) Contact System and Bonding, of $1,610,000 and $1,100,000 respectively, or a total of (I) and (II) amounting to $2,710,000. The output of the substations amounts to only some 47 million kw-hr. per annum. For a load of the character handled on his railway the substation outlay could certainly be reduced to much less than half of his figure. Without going at length into this matter, (which appears to be the chief point of difference between our estimates), I should unhesitatingly reduce Mr. Babcock's $2,710,000 by $800,000. Bond interest at 4½ per cent comes to

$$0.045 \times 800{,}000 = \$36{,}000.$$

and when subtracted from the "Electric" total of $451,000, leaves ..... $415,000.

We now have

Steam	$928,000
Electric	415,000
Difference	$513,000

from which the cost of the electricity is to be defrayed. 55 million kw-hr. delivered annually to the substations at a price of 0.65 cents per kw-hr. amounts to an annual charge of $358,000, leaving a balance of $155,000 to cover taxes and depreciation. The net investment is

$$\$3{,}828{,}000 - \$800{,}000 = \$3{,}028{,}000$$

of which amount our $155,000 is 5.1 per cent.

This is a conservatively prepared statement and is interesting in disclosing (1) the effect of the fuel cost on the result and (2) the influence of the substation arrangements.

I cannot agree with Mr. Babcock's optimistic estimates of the efficiency in his electric alternative and in a close analysis corrections ought to be introduced in this respect which would render the results a little less favorable to electrification. On the other hand, I have taken no account of the decreased outlay for substation labor and supplies which would ensue from halving the number of substations and eliminating the feature of starting up the machinery just prior to the approach of each train.

If my results indicate the general order of magnitude of the investment and operating costs, it would appear that the increased capacity consequent upon the electrification of such a mountain grade railway should be amply attractive to justify serious consideration of electrification on the part of the executives of such roads.

Mr. Roger Smith's contribution contains data of very great value. Engineers will appreciate having available the precise figures which Mr. Smith, the chief electrical engineer, and Mr. G. J. Churchward, locomotive superintendent, of the Great Western Railway of England, have here presented. The Great Western data closely confirm my assumptions and in so far as they deviate therefrom will be of valuable guidance in arriving at more appropriate assumptions in investigations of this sort.

I accept Mr. F. W. Carter's suggestions as very much to the point. Mr. F. C. Merriell alludes to the important superiority of electrical operation as regards immunity from the difficulties attending steam-locomotive traction in extreme cold weather. The point is one of much importance.

With reference to the discussion of steel rectifiers by Messrs. Armstrong and Murray, I should like to refer to pages 136 and 137 of a paper entitled *The Relative Costs and Operating Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems*,* in which I called attention to the useful and useless lines on which such apparatus may be developed. If Mr. Murray will refer to that paper and to his own experiences he will see that there is need for a revision of his statement that "the power houses of the single-phase and continuous-current systems are about a stand-off." Mr. Parshall expresses the opinion that the paper credits the steam locomotive with a better performance than is representative. The criticisms of Messrs. Murray and Wynne, on the contrary, appear to be to the general effect that I have underestimated the performance of the steam locomotive.

It is interesting to contrast the conclusions of Mr. George Hill with those of Mr. Babcock. The former states that his

*TRANS. A. I. E. E., Vol. XXXI, (1912), p. 115.

firm has satisfied itself in the course of its investigations that electrification will make a very satisfactory showing for many cases of heavy mountain grades: the latter has reported on "every mountain railway exit from the Central California valleys, and on other mountain districts in other parts of the West Coast country" and the conclusions have invariably been adverse to electrification.

Mr. Wynne criticises my 78 per cent annual substation efficiency for the mountain-grade service as being too high, and recommends that it be decreased by from 7 to 10 per cent. In Mr. Babcock's paper the annual substation efficiency is taken as 90 per cent. In my opinion this is 10 per cent higher than he could obtain by any practical means for the service he describes. In Mr. Wynne's opinion Mr. Babcock's figure is 20 per cent too high.

I am especially glad to have the data which Messrs. Hall and Welsh give relating to the cost of Mallet locomotives. Although the figures which I obtained for the cost of Mallets were from very reliable sources, nevertheless, I should have employed somewhat lower prices had these further data been known to me. The comparative result would, however, not be much affected, if at the same time, I had taken the electric freight locomotives at $350 per ton, the figure employed by Mr. Babcock in his paper, in place of the figure of $450 per ton which I employed for the electric locomotives in my estimates.

A. B. Babcock (by letter): Mr. Hobart is satisfied "that Mr. Babcock may be in error in extending his unfavorable conclusions as regards electrification of mountain railways to cases where the conditions are less favorable with respect to the low cost of fuel than in the exceptional case which he has considered." It seems impossible for me to make plain enough to be understood that my conclusions are not unfavorable to electrification of any railways, mountain or plain, except those that I have investigated personally and reported on adversely. While these concern the exits from the Central California valleys, and some other mountain districts on the West Coast, there are many other districts in which electrification may be extremely profitable. I am not aware that I have ever made a statement favorable or unfavorable to electrification in general.

Mr. Hobart, if I understand his argument, goes on to assume a hypothetical value of fuel and from that argues himself into a position contrary to that resulting from my analysis of the Tehachapi figures. With reference to this, permit me to call his attention to my discussion of his paper (see page 1237, preceding). "While in the hypothetical case, from a given set of assumptions one may argue himself into almost any desired position, in practise the hard and unyielding physical facts are met." He also states, "For a load of the character handled on his railway the substation outlay could certainly be reduced to much less than half his figure." Again permit me to

call his attention to the fact that actualities are considered in my Tehachapi paper and to refer him to the paragraph wherein I said, "This traffic must be handled as circumstances require. It cannot be spaced conveniently for power demands, as many engineers and power men have suggested, but the terminal yards must be cleared as the cars accumulate."

Mr. Hobart contrasts the conclusions of Mr. George Hill with mine. Mr. Hill's viewpoint and mine are different. Again I will refer him to my Tehachapi paper, first and third paragraphs thereof.

From the foregoing quotations it would appear to me that Mr. Hobart has not read the Tehachapi paper with the care that would justify his positive statements with reference to my attitude. For his information I will state that the said Tehachapi paper was written in the hope that it would draw out a discussion wherein, if my office has been in error for the last ten years with respect to such problems, these errors would now be pointed out by those who are competent to have opinions on this subject. So far only Mr. Hobart has offered a criticism. He appears to have read it without discovering that it deals with facts,—with things as they are, not with things as both he and I might wish to have them. Only a few weeks ago I stated to a representative of a prominent engineering firm that I would be very glad to be shown that my conclusions are erroneous, if such is the fact, and I made the offer at that time, which offer still stands open, that although I had stated in the Tehachapi paper the absolute operating facts as taken from the company's records, I am ready at any time to turn over to competent members of any of the large electrical manufacturing companies, all of the operating data that can possibly cast light on these problems, to give them access to all of the facts in connection with the property, and if they can convince our operating officials that there is a profit in the electrification of any one of the mountain outlets from Central California, as operated by this company, or as can be reasonably operated by this company, I stand ready to confess my error as publicly as I have stated my conclusions; but I will neither take part in general discussions that lead nowhere, nor will I pick up straw men after they have been knocked down.

An address presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright 1913. By A.I.E.E.

SOME ASPECTS OF INSTITUTE AFFAIRS

President's Address

BY RALPH D. MERSHON

The address of the retiring President of the Institute has usually dealt with some aspect of engineering, or with the engineer. It has been the exception, rather than the rule, that a presidential address has discussed Institute affairs. It seems to me eminently fitting and desirable that in retiring from office, the President should record his views on the more important matters affecting the interests of the Institute, with which he has become acquainted as the result of his administration, and the years of service that preceded it. It is my purpose, therefore, to discuss some of the more important problems confronting the Institute, and record my views on them, and on some of the general conditions affecting the welfare of our organization.

All of us, I am sure, desire that the intensity and scope of the activities of the Institute shall continually increase. That new technical committees shall be instituted, as fast as the progress of the art of electrical engineering justifies them. That new Sections shall be formed. That Institute meetings, or Conventions, under the auspices of the Sections, shall be held whenever a Section desiring such a meeting can justify its authorization. In fact, that Institute affairs shall always be so conducted as to best conduce to the progress of the art with which our organization concerns itself. But there is a limitation on the degree of such activities, quite aside from the willingness of the individual members to give the time and energy necessary for them; the limitation imposed by the relation between income and expenditures. Take, for instance, the matter of technical com-

mittees. Whenever a new technical committee is formed it means added expense, principally for printing. It means, under our present method of procedure, that the matter resulting from the activities of the new committee will be issued to each of our 7500 members. It will be issued to each of them twice; once in the PROCEEDINGS and once in the TRANSACTIONS. The increased expense incident to the addition of a particularly active technical committee may, therefore, be quite a considerable item. It is evident that our activities, through technical committees, or otherwise, might be stimulated to a point where our income would not be sufficient to meet expenses. The Institute is approaching such a condition of affairs. The amount of our annual expense is uncomfortably near to that of our annual income. We must, in the near future, either slow down in the rate of increase of our activities, or cut down our expenses, or increase our income. We must either make our activities keep pace with our increase of membership, or decrease the expenses of our activities, or raise our dues. The last course would be highly objectionable, and the first highly undesirable. The second expedient, that of cutting down our expenses, is the only one that appeals to me. I believe it to be feasible, and I am sustained in this opinion by those of our members with whom I have discussed the subject.

Our largest single item of expense is printing. Undoubtedly we spend a good deal more for printing than is justified. From time to time we print papers and discussions whose proper medium is the technical journals, not the Institute publications. Our printing and mailing expenses can be considerably reduced by a more searchingly judicious selection of the matter for publication from the wealth of matter presented before the Institute. They can be much further reduced by devising some scheme whereby each member will receive only that matter which deals with the subjects in which he is interested, with the proviso that he can receive all the matter issued by paying something in addition to his regular annual dues. Possibly, also, we can avoid sending out the same matter twice. Undoubtedly there can be, and should be, devised some expedient, whether along the lines suggested or otherwise, that will be acceptable to the membership and will result in a saving which, for a time at least, will push forward the expense limitation upon the increase of our activities. The membership should assist the governing body in solving this problem.

This question of expense has a bearing, not always clearly appreciated, upon another matter. We often hear expressions of regret that other societies have been formed to deal with subjects presumably falling within the scope of the Institute. But I question whether this is always, or ever, a proper subject of regret.

If a new society be formed some of its members will be men who are also members of the Institute. These members, common to both societies, will pay into the new society dues in addition to those they pay into the Institute. Also, the new society will send out its publications to its own limited number of members.

If the new society be not formed, if the Institute takes up the work, that the new society would cover, with the same degree of intensity that the new society would, the Institute will do this without any proportional increase of income, and will, under our present scheme, send the publication of the new matter to all the Institute members, instead of to the comparatively few of the new society. If it is true that the expense *per member* of the Institute for issuing this matter will probably be less than in the new society, it will not be enough less to counterbalance the fact that the Institute will have no proportionate increase of income, due to the new activity, and to the fact that the published matter will be sent to all the Institute members instead of the smaller number of the new society.

It appears, then, that a new society accomplishes for the art of engineering, generally, two of the possible expedients mentioned above in connection with the Institute. That is, it increases the total income available for technical work, and keeps down the gross expense by sending published matter to those only who are interested in it. It would appear, therefore, that the splitting off of a new society from the Institute is not an unmixed evil. Perhaps there is, and in many cases I think there is, no evil in it at all. Of the members of the new society who are not members of the Institute also, few, if any, would have been members of the Institute if the new society had not been formed, and such additional members as might have been attracted to the Institute by reason of the new activity would not have yielded an increase of income comparable to the increased expense. On the other hand, the formation of the new society will draw away from the Institute few, if any, of its members.

Similar considerations apply to the question of amalgamating engineering societies, of which we hear from time to time. If

engineering societies were brought together in a very general organization of the nature of a holding company, possibly some considerable benefit might be derived therefrom. But if they were to be actually amalgamated into one society, I think it very questionable whether the disadvantages would not greatly outweigh the advantages of such a course.

For a good while there has been a tendency based upon tradition and precedent, to limit the scope of the Institute's work to those merely technical activities which some people seem to think constitute the sum and substance of engineering work. The attitude has been that the engineer is not concerned with dollars; that it is beneath his dignity to deal with them. This attitude has been maintained in the face of the fact that in all important practical engineering work the question of dollars is the very first one involved, whether it be in the construction cost of the work, in the operating expense in connection with it after it has been installed, in the profit to be derived from its operation, or all of these. I believe it is becoming more and more clearly realized that this old point of view is not only narrow, but erroneous; that a technical man is not an engineer unless he is an economist, and that he can not be an economist unless he can, and does, deal with the dollar side of every engineering proposition. This more enlightened point of view is being reflected in the work of the Institute, as is evidenced by the appointment of committees to deal with such things as depreciation, operating costs, etc. It is to be hoped that this tendency towards the liberalization of Institute activities will increase.

The system of local Sections, which has now been in operation in the Institute for ten years, has grown in importance and value, and will undoubtedly continue to do so as time goes on. I consider that some of the most valuable work of the Institute is being done because of the existence of the local Sections and I believe the importance and the value of the work done because of, and due to, the Sections will continually increase. I say this the more gladly because at its inception, and for some time afterwards, I took an unfavorable view of the Section movement, and had grave doubts as to the possibility of the Sections ever amounting to much.

It has been suggested that the Sections be encouraged to make their organizations more formal than at the present time. That they have a system of technical committees corresponding to the technical committees of the national organization, in so far as the subjects with which the national committees deal are of

interest in the part of the country in which the Section is located. It has also been proposed that where a Section has a technical committee dealing with a given subject, the chairman of the committee shall be a member of the corresponding national committee. These suggestions are, it seems to me, worthy of careful consideration. Their adoption would be a means of more closely binding together and correlating the technical work of the national body with that of the several Sections. I have, during the past year, endeavored to realize some of the advantages of such a scheme by appointing to committees men recommended thereto, at my request, by the Sections. The adoption of the suggested interlocking committee scheme would more or less automatically take care of the matter.

But whether the idea of similar technical committees be carried out to the extent suggested or not, it seems to me exceedingly desirable that each Section have a Membership Committee corresponding to the Membership Committee of the national organization. And that hereafter any effort made to acquire members be exercised, not by the Membership Committee of the national organization directly, but by that committee through the several membership committees of the Sections. It seems to me hardly in keeping with the dignity of the Institute to circularize for members. If each Section has a Membership Committee, these local committees will be in a position to campaign for new members, either by direct personal contact, or by enlisting the aid of other members of the Section, who, by personal contact and influence, can bring about the desired end much more effectively than it can be accomplished by means of circulars, and certainly in a manner much more compatible with the dignity of the Institute.

It is desirable that the membership generally take a greater interest in the conduct of Institute affairs, and participate in such conduct, so far as geographical location will permit. Many of the problems arising in connection with the work of the Institute can best be solved with the aid of our members, and they should not only be encouraged but expected to lend this aid. Such general participation would undoubtedly be facilitated if there were a better geographical representation on the Board of Directors than there has been in the past. While I realize that the greater number of the Directors must be drawn from sections of the country from which Institute headquarters are easily accessible, in order that the work of the governing body shall not be hampered, yet it is desirable that a certain number

of the Vice-Presidents and Managers be distributed over the remainder of the country. This could be done, without running the risk of seriously hampering the work of the governing body, if that body were increased by the number of the members to be apportioned to the districts more remote from headquarters. It seems to me that such increase and apportionment is desirable, not only as a means of participation, but as a means recognizing effective service and achievement on the part of members distant from headquarters.

Participation by the members in the conduct of Institute affairs would also be fostered by greater publicity in the matters coming before the Board of Directors. We obviously cannot expect the cooperation of our members, no matter how willing they may be to give of their time and effort, unless they know of the problems on which cooperation, advice, suggestion and criticism are desirable. There has been a tendency to take the attitude that it might be harmful to the Institute if matters on which there were differences of opinion in the Board of Directors became known to the membership. To my mind this is erroneous. I believe no live organization is hurt by discussion, no matter how general it may become. In fact the more open and general discussions are, the more likely is the organization to maintain a healthy condition. If there be vigorous differences of opinion, vigorously expressed, it is an evidence that the organization is alive; and if there be any contention, the more public it is made the more likely it is to be conducted in a spirit of the utmost fairness. For my part, I should much prefer an organization live enough so that its affairs would evoke discussion, than one so dead that no discussion or contention would ever have place. Discussion, constructive criticism, even contention, when it involves matters of principle, are evidences of the vitality and worth-whileness of the organization, and not evidences of disintegration, or any tendency thereto. I believe it much better in every way for the Board of Directors to allow members to know of any considerable differences of opinion that may arise in the Board, than to endeavor to cover them up under the mistaken idea that harm to the Institute may result from their publicity. The Board should have nothing to fear from publicity. If it has anything to fear, that is all the more reason why the members should be apprised of the matter at issue.

Much of the opposition that is at times evidenced in new departures on the part of the Institute, and many of the criticisms

of current courses of procedure, are based on precedent and tradition. While I believe precedent should always be considered, I see no reason why it should not be promptly overruled if contrary to any course that on careful consideration appears advantageous and desirable. Precedent is, it seems to me, mainly valuable as causing us to more carefully consider a course proposed contrary to it, or as the basis for a decision in doubtful questions. The most striking and valuable improvements have almost always come as the result of action directly contrary to all precedent. The criteria of yesterday will not necessarily serve for today; and the criteria of today will probably not all serve tomorrow. There is no more reason why we should necessarily conform to the practise of others, or to our own practise in the past in Institute affairs, than there is in any of the other affairs of life. For instance, society is coming to see the futility and false modesty of endeavoring to blink certain physical facts in connection with human nature. It is coming to realize the false modesty and almost criminality of endeavoring to ignore those things which nature will not permit to be ignored except under penalty, and as a result some matters are now openly discussed with a frankness that would have caused our forbears to hold up their hands in horror. There is no reason, that I can see, why in Institute affairs, any more than in the other affairs of life, we should hesitate to do those things that are obviously both fundamentally right and expedient, no matter what tradition may be outraged, or how contrary such course may be to previous custom and usage.

There have been criticisms of some of the present methods of conducting the affairs of the Institute which I think should be viewed in the light of what I have just said, rather than in the light of precedent. One of these is the matter of anything of the nature of competition for the offices in the gift of the Institute. To my mind a spirit of competition is to be welcomed rather than frowned upon. The offices of the Institute are no sinecure. The officials and others conducting the affairs of the Institute are directly responsible for the results obtained, and in order that effective results shall be forthcoming it is necessary that they devote a considerable amount of time and energy to the work their tenure of office implies. It is a matter of congratulation, therefore, it seems to me, that there should be competition for an opportunity to do hard work. It is evidence of the live condition of the Institute, and of its capability for accomplishing

results. To my mind it is a great deal better both for the Institute and the individual office holder that the latter attain his office as the result of his frankly evidencing his desire for it, and if necessary competing for it, rather than under the fiction, that no one believes, which would make it appear that he is prevailed upon to accept the office only through the urging of his friends.

There has been some objection to the circularizing which has sometimes been resorted to in connection with the election of officers; the idea being that it were better if the nominations were quietly made, by a selected group of men, and the election conducted without any possibility of opposition. In other words, that, in effect, the officers of the Institute should be chosen by a selected few instead of by the membership at large. I have even less patience with this point of view than with that just cited. To put a ban upon circularizing would be to throw the power of nominating and electing into the hands of those who might be in position to control these functions without the necessity of circularizing, by virtue of their ability to avail themselves of organizations outside the Institute, or by their control of organized cliques within the Institute. To forbid circularizing would absolutely tie the hands of those independent of any other organization, or of any clique, and would tend to put a premium on the control of the Institute by oligarchy.

There has at times been evidenced a tendency to elevate to the high offices of the Institute men who have done little, if any, work for the organization. To my mind this not only works an injustice upon those who have given the Institute their best efforts, but is against the best interests of the society in every way, especially if the individual's chief claim to prominence arises from activities in fields other than that of electrical engineering as defined by the Institute's constitution. One of the incentives to effort on the part of the individual members of the Institute is that of the possibility of recognition of such effort through appointment, or election, to some official, or semi-official, position. I am quite aware of the fact that in some quarters this is not admitted, and that such sentiments as this are taboo. But to convince himself that the statement I have made is a true one, one needs only to ask any individual who has labored faithfully for the Institute, whether in case it had been possible for him to have done the work accomplished without the remotest chance of his name ever being known in connection with the results attained, he would have been willing to labor as faithfully for

their attainment. In almost every case, if not every case, an honest answer will compel the statement that he would not.

It is the young man starting into his life work that we especially desire to attract to the Institute. Young men starting the struggle for existence have scant opportunity for devoting themselves to things other than those which will immediately forward their interests. Later on, when a certain amount of success has been achieved, they may indulge in the luxury of altruism, but until such measure of success has come to them they are neither justified in indulging in the kind of altruism that unrequited Institute work implies, nor are they willing to do so. It behooves us, therefore, to make service in the Institute as attractive to them as possible, and to this end we should so guard the offices of the Institute, elective and appointive, that they may be the reward, not only of achievement in electrical engineering, but also of service in the Institute. That the membership will feel that the criterion of fitness for these offices shall be not merely prominence, however great, but also a generous measure of previous effort in forwarding the interests of the Institute and the principles for which it stands.

Remarks similar to those I have made in regard to the Institute offices will apply to the question of membership in the Institute, and preservation of the highest standard for the various grades laid down in our constitution. In discussing the eligibility of candidates for membership whose qualifications do not seem to square with the requirements of our constitution, but who are prominent in some lines other than those covered by our constitutional requirements, those favoring the candidate often make statements as to his great ability and express their belief based thereon that he is entitled to membership. These people lose sight of the fact that the requirements for membership in the Institute are not a question of the opinion or belief of any individual. They lose sight of the fact that the requirements for membership have been agreed upon by the members of the Institute and are laid down in the constitution. The only opportunity, therefore, for opinion or judgment is as to whether the candidate meets these constitutional requirements. If the constitutional requirements are not what they should be, and if the membership comes to the conclusion that they should be other than they are, then they should be changed; but so long as they stand, they, and only they, should be the standard by which to measure eligibility.

I quite realize the fact that from the point of view of a few some of the things I have said not only are unorthodox, but border on heresy. I believe, however, that my views will be concurred in by a large majority of the membership. If they are not, then I cannot expect them to be of any effect or influence. If they are, I sincerely hope they may have an influence on the future course of Institute affairs.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright, 1913, By A. I. E. E.

A SUGGESTION FOR THE ENGINEERING PROFESSION

BY WILLIAM McCLELLAN

The engineer of today traces his ancestry along two distinct lines, one practical, the other theoretical. In times past what we call engineering was done either by a skilled mechanic or by a scientist having a practical bent. As the demand became more and more complex, and as science opened up wider and wider fields of knowledge, the mechanic became more and more skilled in certain ways and some scientists became more and more practical. The merging of these formed a group of workers, having common aims and now known as engineers.

The skilled mechanic, however, from the standpoint of quantity, was by far the larger element. One need go back only to pioneer or colonial days to learn that practically all of the engineering, as we know it, was done by the surveyor, the millwright, the master carpenter, the master mason, the smith, and others. Even now, many a smith claims to be able to forge without plans, a hook equal to any that a mechanical engineer can design, and many a country carpenter will frame quite complex roofs of a variety of types, all "out of his head."

Passing quickly over many interesting details, we find that more or less on account of their industrial lineage, engineers are divided into classes. Once there were two of these, civil and military. Later, starting with the multiplication of engines and machines, the civil class divided up into the almost innumerable varieties of engineers which it is unnecessary to list here—if we could.

As a result, while there are many men of great breadth of mind and experience worthy of the title of "engineer," there

is no one who can claim it in the same way that lawyers and doctors can claim their titles. There are engineering professions, but there is no one profession. There are engineering degrees, but there is no one engineering degree. There is no engineer without an adjective. It must be acknowledged that there is some truth in the charge of "lack of breadth," considering the whole body of engineers. It is also curious that in medicine and law the students leave school all with the same general training and degree, but specialize afterwards, whereas in engineering they are specialists at school.

So far as individual activity is concerned, engineers are of different types in the same way that lawyers and doctors are, but to a greater degree of demarcation. Today all the numerous classes of engineers contain three distinct types of members:

First, the theoretical engineer, who in reality is not an engineer. He is, and it would be proper to call him, an applied scientist. Many of the engineers in our great electrical manufacturing companies are in this class.

Second, the mere manual and mental operative, the hewer of wood and drawer of water in the engineering world.

Third, the real engineer who can design and create, who can adapt the resources of nature efficiently to the service of man.

In passing, it may be remarked that the presence of these three types in each class of engineers is the chief difficulty in arranging proper courses in engineering education.

The intensely practical result of all these causes is that engineering is not securely established as a profession; it is difficult for the engineers of the country to act as a unit where united action would be of benefit to society; the engineer is handicapped in obtaining recognition and authority when working jointly with men of other callings and professions; and finally, on account of its divisions, the development of the profession as a whole is proceeding slowly and inefficiently, resulting in an economic loss to society.

Many will remember how often within the last few years a demonstration or recommendations by a united engineering profession would have been valuable. Society needs such help in connection with conservation discussion, appointments of the many municipal, state and national commissions involving engineering in some form, opposition to ill-advised or vicious laws, methods of conducting public work, and a variety of other similar matters.

When unity is so desirable or even necessary, a great effort is worth while to obtain it, but the question is, how?

We might turn to the colleges and technical schools. I have suggested before, and long to see the time, that some prominent school shall offer the degree of Bachelor of Engineering, and give all such students the same general course with a very small percentage of special electives. The schools are moving in this direction and we should have great faith in them. Of necessity the progress is slow and will not answer immediate needs. If revolutionary changes were possible at once, the effect would not be seriously felt for years. The schoolmen must be given time to work out their plans. Outside engineers may occasionally offer valuable suggestions but they are much less able to attack the problem than those whose business is to study it at close range.

If custom were followed, where it is desirable to get united action in some one direction, a great national society of engineers would be organized to which all properly qualified engineers would be eligible, irrespective of their adjectives. Many men have thought of this, but for a number of reasons it is not practicable. There are a large number of "adjectival" societies now, to which great numbers of engineers have given their allegiance. No one society could be formed without having at least four sections equal in importance and influence to the four great national organizations.

One of the four principal societies having an honorable and distinguished history claims to be such a general society, and its constitution provides for the admission of any engineer having sufficient proficiency in his line. The claim to the title can be only nominally upheld, however, because the connotation of "civil" engineer today is so well known to everyone that it is not even necessary to discuss it.

What then can be done? Unity we need badly—unity we ought to have. I have sometimes thought that if a great organizing genius, such as is discovered occasionally in the industrial world, were to undertake the problem, he might build a merger out of or on top of the present organizations, which would leave them organically intact, but provide for united action in general fields. Engineering might have a federal government. It is to be feared, however, that the time is not ripe. Nevertheless there is every reason why we should work toward such an ideal, and the following suggestion is offered. To make it perfectly clear, some details must be given, but there is no insistence on these as essentials, though some of them probably would be. The sugges-

tion is to form a national body, representative in its membership, of all national engineering societies. All trade and business organizations to be excluded. The content of the suggestion can be most easily given by a skeleton constitution as follows:

Name. American Engineering Association.

Object. To assist in the realization of the ideals of the engineering profession and to extend the usefulness of the professional engineer as a servant of the community.

Membership. Any national society of professional engineers, with or without associated grades of membership, to be eligible. No personal membership. Member societies to elect representatives annually on a numerical basis, *e.g.*, one representative for 3000 members or less, and one representative for each additional 1000 members. Representatives to have terms of three years and to be ineligible for re-election. Terms to be arranged in rotation groups. Officers to be elected by representatives annually.

Support. To be by annual assessment of member societies on per capita basis.

Functions. To arrange an annual convention of engineers for discussion of engineering in general, of the engineering profession, and of any related subjects, except scientific and technical subjects such as would naturally and properly come before meetings of member societies.

To hold not less than two other meetings each year at which the objects of the association would be discussed and recommendations forwarded to the member societies, if desirable.

To investigate and report on, with recommendation, any subject which might be referred to it by a member society.

To appear at congressional, legislative or other hearings where it may be desirable, for the purpose of assisting in a proper decision of questions affecting the public good.

To make recommendations at any time to public officers as to policy in relation to matters in which the engineering profession may be interested on its own account or on account of its share in responsibility for public progress.

As the title states, this is merely a suggestion offered, in brief form, to provoke discussion. Everyone will probably agree that the subject is a most serious one and worthy of attention. Should the suggestion be received favorably it could be referred to the Board of Directors. No attempt should be made to carry any such scheme into effect until at least three of the four great national engineering societies could endorse the final plan.

DISCUSSION ON "A SUGGESTION FOR THE ENGINEERING PROFESSION" (MCCLELLAN), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

C. O. Mailloux: Mr. Chairman and gentlemen, I regard this paper as one of the most interesting papers that has been presented to the Institute for some time. The President has said that this is *the method* of raising the social status of engineers. I look upon it as *a* method, because I think there are many methods. I have looked forward for many years to greater co-operation among engineers. It has been one of my hobbies. There has been a tendency among engineers to segregation; the different bodies have tended to undergo a process of evolution in different directions, in many respects, in regard to their points of view, and their attitude towards public questions, and also even in regard to their ethics and their methods of professional discipline and conduct. Many engineers in the different branches of engineering realize this, and they also realize the importance of doing something to improve conditions; and various remedies to overcome the conditions that now exist have been proposed.

The American Institute of Consulting Engineers, which has recently come into some prominence, has attempted to bring together the different branches of the engineering profession into a body that will work for the profession of engineering in general. That body is interested more specifically in the welfare of consulting engineers, which is well enough, as far as it goes, but is, perhaps, not as good as it might be if it were sufficiently comprehensive to include engineers of all types, for there are many prominent and eminent engineers who are not consulting engineers, and can not be properly classed as such. I think the suggestion of Dr. McClellan is a very good one indeed. In the way he has formulated it, it is very excellent, but I am not so severe as he is inclined to be as to the means of carrying it out. I think the matter should be carried out by the Institute. It has been the pioneer of progress in the development of many good ideas in this branch of engineering, and in other branches of engineering, generally.

We have inaugurated the Section movement, which is being taken up by other branches of the engineering profession, and I do not see why this body should not be the fostering spirit of a movement of this kind, looking to coöperation among the different branches of the engineering profession.

I would like to make a motion that this matter be referred to the Board of Directors, as I consider it well worth the closest attention of the Board of Directors; and it should serve as the basis of a thorough study and investigation of the question, the Board of Directors to be given full power in the matter, and to indicate to the membership its conclusions in due course.

Oberlin Smith: As a long-time member of all four of the big engineering societies, I feel that perhaps I can speak on

this subject impartially, although I happen to be more closely related with the mechanical engineering branch than any other.

For many years past progressive engineers have hoped for a united engineering society of some kind. The movement was brought up some time ago, before the Engineering Societies Building in New York City was constructed, and the plan freely discussed, but with some of the societies there was too much of a clannish spirit to permit full and complete coöperation; hence nothing practical was done at that time. When, however, Mr. Carnegie gave us the building on 39th Street, many of us hoped that all four societies would come in. The fact that one of the societies remained out was a great disappointment, but I know that many members of the American Society of Civil Engineers much regret the separation. Last week at a convention of the Society in Ottawa, this feeling was brought out strongly and there was some manifestation of the spirit which has been shown in this splendid paper of Dr. McClellan's. The new president, Prof. Swain, of Harvard, gave us a most effective and interesting address. There were some things in it which seemed to be too conservative, yet he took a broad view of the subject, and regret was expressed that the various societies had not all gotten together before. At the meeting, however, there was in evidence some of the old idea that civil engineers were most important, because they covered all the ground outside of military engineering.

It seems to me that we all might get nearer together by mixing, so to speak, the councils of the different societies. Some members of the Mechanical Engineers who are also members of the Electrical Engineers should be in the Council of the Electricals, and vice versa; and this system of mixing of interests would certainly tend towards greater unity and efficiency.

Thus in the Council of each Society, there would be a few of the best-known and most fit members of each of the other societies.

There have, so far, been but few electrical, mechanical, or mining engineers represented on the Council of the American Society of Civil Engineers. I do not remember whether there are any now. Under such conditions a society can hardly claim to be at the head of all engineering activities.

I think, however, that the feeling is growing all the time, among the members of the various societies, that there should be a greater coming together, but they are not limited to the four old organizations above mentioned.

We have among them an important society, the Naval Architects and Marine Engineers; and we have numerous smaller societies, like the Society for Testing Materials, the Society for Engineering Education, the Illuminating Engineering Society, and similar organizations. We are one family subdivided into smaller branches. Of course, there are all kinds of specialties in engineering, just as there are in other professions. Spec-

ialization is increasing all the time, and must be expected. No one man can acquire thoroughly all engineering knowledge. If he knows his own specialty well, and knows about other things in only a general way, he will be likely to make a successful engineer.

I thoroughly agree with Dr. McClellan's idea that we should make some beginning and start in to organize a United Engineering Society. It would probably be impracticable to make the membership of individuals, but it could be made up of other organizations, as suggested. There is no reason why it should not be a unit by itself and have its complete individual organization, with its own separate meetings. Not only could such a society handle the matter of ethics, which has been so well taken care of by this society, but it could make suggestions for better laws and better government in all sorts of ways; and it would have a broad influence, scientific, economic, moral and social, which engineers do not now possess. We could exert our influence in a powerful way by united strength, rather than individually, as we now do. I look forward to such a movement being a wonderful success.

Chas. L. Clarke: Dr. McClellan seems to be in doubt as to whether the time is ripe for an organization of this sort. Undoubtedly the time is here, and we ought to see such an organization founded before long. The danger that it might interfere with the so-called clannishness of the member societies, is hardly possible, because the plan does not propose interference in any way with the technical business or other individual matters of such societies, but only contemplates fostering national and broad policies affecting the body politic in general, as far as engineers can help to do so, as men of education and of technical judgment.

Dr. McClellan has invited suggestions on two points. The speaker has one suggestion to make with reference to the name of the society. According to the suggestion in the paper of Dr. McClellan, it is to be called the American Engineering Association. The speaker proposes that it be called the American Association of National Engineering Societies, which title seems to explain as briefly as possible what the Association is in fact, and is calculated favorably to attract attention of Congressmen when receiving a communication relative to pending legislation sent to them by this proposed Association, for they will see just what it stands for and comprehend the situation from its name, especially if coupled with a list of its members.

D. B. Rushmore: We received a great deal of inspiration from the Address of the President this morning, and we have also been greatly impressed by the suggestions made by Dr. McClellan in his paper, and these things together lead me to believe that there is very great necessity now for some one to take these ideas and reduce them to general principles, so that the best results from coöperative effort may be secured therefrom. However, I am afraid that we are getting into a

condition of over-organization all over the country. If we take our political life, our industrial life, our social life, and our professional life, we will find that we belong to a great many more organizations than we can take an active part in.

Here we have a very interesting proposition brought forth, and the question arises: What is its practical value? Can we express in general terms this particular hope we wish to accomplish? To a person who has had to work in a large organization, and possibly not especially fitted to adapt himself to others, it has been necessary many times to think— Why an individual? Why a department? Why an organization? And what is it trying to do? All over the country you see rising up industrial organizations, political organizations, and agricultural organizations. In the agricultural organizations an interesting development is taking place. In these organizations a differentiation is being made between those things most efficiently done by individuals and those best accomplished by coöperative effort. They are being organized from beneath upward, the individual action extending as far as efficient results justify it, and further on coöperative effort is substituted, with the most beneficial results for all concerned.

In our field of engineering activities we have a large number of small societies, all actively engaged in fields of special effort. A similar result could be accomplished by joining all of these in one large holding company, and instead of separate entities, having them as members of one large whole. It is, however, a question, and a serious one, as to which method of organization will produce the better results.

It is absolutely essential for the future welfare of the engineer that he should not allow himself to be pushed into the field of an exclusively pure scientist, but that he demand that his work include the consideration of money expenditures, which factor is one of the basic principles of engineering practise.

The standing of the engineering organizations and their value to their membership will depend upon the part which these organizations play in the field of industrial, social and political activity. It is most important that an unrelenting fight be waged against the licensing of engineers by the State. We should insist that the membership rank of the engineering societies be accepted as the means by which the standing of an engineer in his own profession shall be judged. This means that considerable revision must be made of the grades of membership and the requirements for admission to such society.

Dr. McClellan's suggestion has much of value and is of interest to all engineering societies. It is worthy of much consideration, but it is suggested that it receive the benefit of all possible criticism before we organize another society.

C. L. deMuralt: I am very much pleased with Dr. McClellan's paper, and heartily endorse what Mr. Mailloux has hinted at, namely, that it is just about the right time to have this sug-

gestion made. Dr. McClellan has put it in very good form, even down to the details.

If I say anything at all, it is because I desire to make an additional suggestion: Why is it necessary to add to the many existing societies a new one? Why can we not use one which is already in existence?

The American Society of Civil Engineers is unfortunate in that its name, according to present usage, seems to cover one branch of the engineering profession only. That is not so. Many of us are members of the Americal Society of Civil Engineers, and the American Society of Civil Engineers has always taken the view that it is the old mother society which represents all engineers in this country. Why should we not approach the American Society of Civil Engineers through our Directors, perhaps in coöperation with the American Society of Mechanical Engineers, the Society of Naval Architects and Marine Engineers, the American Institute of Mining Engineers, and similar bodies, and discuss with them this proposition which Dr. McClellan has made.

I am not authorized to speak for the American Society of Civil Engineers, but many of the members of that Society have told me they would like to have the support of the individual engineering societies. I have no doubt they would listen to any reasonable suggestion of having the individual societies come in with them on some broad basis. This could either be done as Dr. McClellan's paper suggests, through a lump sum payment from each society or else by allowing the individual members, if they want to join the American Society of Civil Engineers, to obtain membership by paying some agreed-upon additional fee. I think that along these lines something of real practical value could be accomplished in the direction of Dr. McClellan's suggestion.

C. O. Mailloux: I want to say a word on this question of the role or function which the American Society of Civil Engineers might have played. The American Society of Civil Engineers had the opportunity to lead all the engineering societies of this country, but lost that opportunity thirty or forty years ago, and it is too late to go back to it. The suggestion which Mr. de Muralt made would meet with enormous opposition in the minds of a few fossilized civil engineers who believe in the lion and the lamb lying down together, provided the lamb is inside of the lion. When the lion has become a small thing, dwarfed, in comparison with the lamb, the suggestion is preposterous. I am second to none in my respect for ideals in engineering, and I think I have done my share in the work of raising the ideals of engineering. I know we cannot accomplish the objects which Dr. McClellan seeks to accomplish by proceeding along that line, for the reason that the very things he seeks to have done, namely, the pursuit of ideals, the participation of the engineering profession in the consideration and determination of public

questions, are notoriously the very things which the American Society of Civil Engineers has always dodged and kept away from, and on which it has been afraid to hold distinct and pronounced opinions.

C. L. de Muralt: That, of course, is an individual opinion. It may be shared by many here, but I do not quite see why my proposition is necessarily ridiculous and preposterous. The American Society of Civil Engineers might have had some fossilized members thirty or forty years ago—I was not an engineer at that time—but it does not seem to me fair to cast reflections upon the present membership of that Society on the basis of what happened thirty or forty years ago. I know, as a positive fact, that those who are now managing that Society are not fossilized and I have reason to believe that they are very much in favor of such a movement. They should be approached to find out if it is not possible to carry out Dr. McClellan's idea, without starting a new and unnecessary society.

Oberlin Smith: The American Society of Civil Engineers was, I think, the first engineering society of consequence established in this country. I have great respect for it as a body, but it constitutes only one branch of the profession. Applied to their branch only, the term "Civil Engineers" is a misnomer, and does not mean anything, because most of the rest of us are also "civil". The term was of course used in contradistinction to the term "military engineers," and was applied to all engineers other than those engaged in military work. Although not logical as at present used, it probably will remain with us, but it cannot be a comprehensive name for a united society. If we have a new society, we should not call it "The American League of National Engineering Societies." We rarely could spend the time to pronounce the whole name, but would call it by its initials. Witness the sad case of the American Society for the Prevention of Cruelty to Animals; we always call that the A. S. P. C. A. and then have to think it out. There is a great advantage in having a short name for a society or other organization so that people will be able quickly to remember what the initials stand for. We should have "American Engineering League," or some such name, the shortest that we can get. If a Congressman or such should not know what A. E. L. stood for, we could have the full name presented for his notice, far better than we could a very lengthy one.

D. C. Jackson: This paper has much of suggestiveness in it, and it proposes one of those things which ought to be put into execution. It is one of those things which has been discussed year after year for a long period of time. I hope that Dr. McClellan's entry into the lists will result in the accomplishment of the purpose. I am with him thoroughly, but I want to criticize his paper in a small way.

We generally recognize, I think, that the old definition that comes down from Tredgold, that "Engineering is the directing of

the forces of nature to the use and convenience of man," is a correct definition and sufficiently ample and comprehensive of all modern engineering practises of today. If it is a correct definition of engineering, then what are engineers? I have put the definition of engineers as "Those who are competent to conceive, devise and organize the directing of the forces of nature to the use and convenience of man." If that definition is correct, then it is not quite fair to our profession to eliminate therefrom (as Dr. McClellan's classification purports to do) some of the men who are working distinctly on the scientific aspects of engineering and doing little towards direction and execution. We must include within the profession those men who are scientists primarily, and engineers secondarily, or vice versa. We must also to some degree go over to the other side and include some men who are executives and administrators of engineering enterprises, and also men of engineering ideals and views although their active work may be done in the laboratory or school; in other words, we must make our definitions and our ideals of the profession as comprehensive as may be necessary to take in all these men. This is scarcely a criticism of Dr. McClellan's admirable paper, but a suggestion of the way in which his proposed classification should be modified.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright, 1913. By A. I. E. E.

TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND

BY A. E. KENNELLY AND F. W. LIEBERKNECHT

It is the purpose of this paper to describe in detail a series of measurements of voltage and current made, in February, 1913, over an artificial telephone line 800 km. (nearly 500 miles) long. Although it is possible to compute the behavior of such a line when its electrical constants are known, yet this is the first time, so far as the authors are aware, that an artificial aerial line has been measured both as to amplitude and phase of voltage and current, with less than 2 volts of 750 cycles-per-second frequency impressed at the sending end.

The artificial line used in these measurements is the one permanently installed in the Graduate School of Applied Science at Harvard University, and described in our paper before the Boston Convention of the A. I. E. E. last year, in relation to a-c. power-transmission.[1] In order to convert this artificial line, originally designed as a power-transmission line, into an aerial telephone line, small non-inductive resistances were uniformly inserted in the line, one to each section.[2] These resistances added 100 ohms per section of 80 km., or increased the nominal linear resistance from about 0.3 ohm per wire-km.,

1. *Measurements of Voltage and Current over a Long Artificial Power-Transmission Line at 25 and 60 Cycles per Second*, by A. E. Kennelly and F. W. Lieberknecht. TRANS. A. I. E. E., Vol. XXI, p. 1131.

2. These resistances were made of about 6 meters of No. 32 A.W.G. *Ia-Ia* (0.2 mm. 0.008 inch bare diam.) double-cotton covered resistance wire, and were wound non-inductively on fiber strips 8 cm. long, 2.5 cm. wide, and 0.3 cm. thick, soldered to terminals on the same, and covered in solid paraffin wax. These resistances carry 0.5 ampere without serious heating.

(0.48 ohm per wire-mile), to about 1.55 ohms per wire-km. (2.5 ohms per wire-mile), corresponding approximately to one of a pair of copper overhead telephone wires of copper 3.75 mm. (148 mils) in diameter. That is, one and the same artificial line of coils and condensers can be made to serve either as an artificial aerial power-transmission line, or as an artificial aerial telephone line, by respectively cutting out or in the non-inductive resistance attached to each section, thereby changing the line for low frequencies from about No. 0 B. & S. gage (8.3 mm. 0.325 in. diameter) to No. 7 B. & S. gage (3.65 mm. 0.144 in. diameter).[3] The total available length of line in each case is 2400 km. (1491 miles), only 800 km. (497 miles) being employed in the tests here reported.

For the constructive details of the line reference may be made to our paper of last year already cited.[4] It may suffice to say at

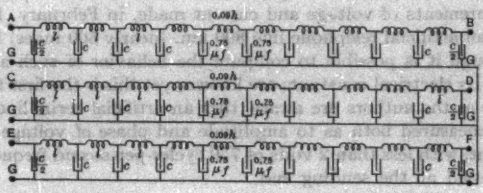


FIG. 1—DIAGRAM OF CONNECTIONS OF ARTIFICIAL LINE

this time that the line used was a Π-line of ten sections, with ground return, the connections being indicated in Fig. 1. The constants for the line appear in Tables I and II. In the design and construction of an artificial ærial telephone line *per se*, not intended to serve also as a power-transmission artificial line, it would be unnecessary to use as much copper as in the artificial line here described. It would also be desirable to subdivide the inductance and capacity into smaller but more numerous sections for frequencies much above 1000 cycles per second. In the line

3. The line actually behaved, at telephonic frequency, like one of a pair of No. 9 A. W. G. copper wires (2.9 mm., 0.114 in., diam.), owing to the combined influences of capacity between the layers of the coil winding, and the lumpiness of the line-section. See Table VI.

4. See also an article "Artificial Power-Transmission Line," by A. E. Kennelly and H. Tabossi, *Electrical World*, New York, Feb. 17, 1912, giving the constructive details of the artificial line.

here described, there were five sections per actual wave-length, at 760 cycles per second.

It will be observed that whereas the apparent inductance of the artificial line is the same at both telephonic and lighting frequencies, the apparent leakance is more than ten times greater at the telephonic frequency while the apparent resistance is nearly four times less, and the apparent capacitance 11.3 per cent less. In other words, the effect of increasing the testing frequency on the artificial line from 60 to 760 cycles per second, is to change all the constants except the inductance. Each coil

TABLE I
ELECTRICAL CONSTANTS OF TEN-SECTION ARTIFICIAL LINE AT 60 ~

	Resistance at 20° cent. ohms	Inductance henrys	Capacitance microfarads	Leakance micromhos	Hyp. angle hyps.
Whole line....	1256	0.913	7.5	120	1.08 /71°.5
Per section..	125.6	0.0913	0.75	1.2	0.108 /71°.5
Per wire-km.	1.57	1.14×10^{-3}	9.38×10^{-3}	0.15	0.00136 /71°.5
Per wire-mile	2.53	1.84×10^{-3}	15.1×10^{-3}	0.24	0.00219 /71°.5

TABLE II
ELECTRICAL CONSTANTS OF ARTIFICIAL LINE AT 760 ~

	Apparent resistance at 20° cent. ohms	Apparent inductance henrys	Apparent capacitance microfarads	Apparent leakance micromhos	Hyperbolic angle Hyps. /_	Surge impedance ohms /_
Whole line..	330	0.9136	6.656	1660	12.94 /79°.5	465 \11°
Per section...	33	0.0914	0.6656	166	1.294 /79°.5	465 \11°
Per wire-km...	0.413	1.14×10^{-3}	8.32×10^{-3}	2.075		
Per wire-mile..	0.665	1.84×10^{-3}	13.4×10^{-3}	3.34		

behaves as though its resistance were 33 ohms instead of 125.6. Its condensers (paper dielectric) behave as though their capacitance had fallen 11.3 per cent while their leakance had risen some ten times. It is known that paper condensers are subject to such changes with rise of frequency.[5] The great apparent reduction in coil resistance can, however, only be attributed to to the effect of the lumpiness of the artificial line. This

5. "The Capacity and Phase Difference of Paraffined Paper Condensers as Functions of Temperature and Frequency," by Frederick W. Grover, *Bulletin of the Bureau of Standards*, Vol. VII, No. 4, February 28, 1911.

deduction was supported by tests made on the coils alone, at telephonic frequency.

Generator. The alternator used was a Cahill multifrequency generator employing a number of stator armatures side by side, with internal rotor field magnets on the same shaft, giving respectively 2, 4, 8, 16, 32 and 64 cycles per revolution. It was directly coupled through a leather-strip coupling to a 500-volt, four-kw., four-pole direct-current motor. Each of the component alternator armatures was rated at about 500 watts output. Only two of the armatures were used, namely, those giving 2 and 32 cycles per shaft revolution. When running at 1425 rev. per min. or 23.75 rev. per sec., these armatures delivered frequencies at 47.5 ~ and 760 ~ respectively. The former was used to supply a Frahm vibrator frequency indicator, and the latter for the test of the artificial line. When the frequency meter indication was steady at 47.5 ~, the artificial-line frequency was known to be 760 ~. By leading the shunt-field circuit of the

FIG. 2—CIRCUIT CONNECTIONS OF ARTIFICIAL LINE

driving motor into the artificial-line room, an adjustable field rheostat in this room enabled the driving-motor speed to be kept constant, and thus also the alternator frequencies.

Frequency. The reason for selecting 760 cycles per second for testing the artificial telephone line was that this is near to the standard telephone frequency of 5000 radians per second (795.8 ~) which has been accepted internationally. It is also known to be near to the fundamental frequency of the diaphragms of the standard receiving telephone used.[6]

Circuit Connections. The circuit connections of the artificial line are indicated in Fig. 2. The alternator stator armature *D* delivered 40 volts at 760 ~ in the testing room. A step-down

6. "The Impedance of Telephone Receivers as Affected by the Motion of Their Diaphragms," by A. E. Kennelly and G. W. Pierce, *Proc. Am. Ac. of Arts and Sci.*, Vol. XLVIII, No. 6, September, 1912, p. 113; also *Electrical World*, New York, September 14, 1912; and "The Humming Telephone," by A. E. Kennelly and W. L. Upson, *Proc. Am. Phil. Soc.*, 1908.

transformer, $P\ S$, lowered the voltage to about 1.75 volts at secondary terminals $G\ Q$. The adjustment was made by inserting an adjustable reactance X in the primary circuit, partly for the purpose of reducing upper harmonics in the wave of secondary voltage. The voltage wave-form was somewhat peaked. That is, a symmetrical third harmonic was perceptible; but no analysis of the wave form was attempted. The secondary terminal Q was connected to the end A of the artificial line through a non-inductive resistance R of 100 ohms. The other secondary terminal G was connected to the ground return of the artificial line, and was also carefully grounded.

Three series of tests were made, namely, with the distant end of the line (1) freed, or open, (2) grounded, and (3) connected to ground through a standard subscriber's set.

The third condition is indicated in Fig. 2.

Telephone circuits actually employ metallic return, and not ground return; but all tests on ground-return artificial lines are immediately interpretable on metallic-return or loop basis. These tests correspond to applying 3.5 volts at the sending end of a loop, and two subscriber's sets in series at the receiving end.

Method of Measurement and Apparatus Used

The potential and current along the line in the steady state were measured by means of a Drysdale a-c. potentiometer, using a Duddell vibration galvanometer. The Drysdale instrument was described with some detail in our A. I. E. E. paper of last year, above-mentioned. Since the potential on the line nowhere exceeded 1.8 volts, the potentiometer was able to read the potential at any junction point directly, without the intervention of a multiplier or step-down transformer. In order to find the current strength, the drop of potential in the 100-ohm inserted section-resistances was measured.

The Duddell vibration galvanometer[7] was tuned to the testing frequency and operated with the aid of an arc lamp. The spot of light was thrown on a white wall several meters away, so that it was easy to see when balance was secured and the spot of light brought to rest, from almost any part of the testing room.

The 760-cycle-per-second voltage was raised to nearly 140 volts by a step-up transformer, and impressed on the split-

7. "A Bifilar Vibration Galvanometer," by W. Duddell, *Proc. Physical Society*, London, May 14, 1909 and *The Electrician*, London, Vol. LXIII, pp. 620–622, July 30, 1909.

phase angle measurer of the instrument. The phase balance required about 0.043 microfarad and 340 ohms, inserted in the associated shunt circuit of the split-phaser. This split-phase balance had to be checked and adjusted occasionally.

Method of Observation

In making a series of tests along the line, the impressed e.m.f. and frequency at A, Fig. 2, were kept as nearly constant as possible. One observer watched the Frahm frequency meter, another changed the potentiometer leads along the line and watched the vibration-galvanometer arc-lamp. A third adjusted the potentiometer balance for amplitude and phase. Each voltage could ordinarily be measured to 0.001 volt, or closer, in amplitude and to a tenth of a degree in phase. This voltage represented either a potential from some junction point on the line to ground, or the potential drop in a section of 100-ohm resistance. In working out the results, they were all reduced by simple proportion to what would have been observed if the impressed e.m.f. at A had been just $1.00 \underline{/0^\circ}$ volt instead of the 1.7 volts, or thereabouts, actually measured. This reduction was made for greater simplicity in presenting the results.

Results

The results obtained are indicated in Tables III, IV and V for the condition, at the B end, of grounded, open, and through subscriber's set, respectively. Referring to Table III, the first column denotes the test-points along the line. Arabic numerals designate junction-points between sections, and Roman numerals mid-section points (see Fig. 2). The distances in kilometers of these points from the distant end of the line appear in column 2. The hyperbolic angle δ, of each point from B, is given in the next column, expressed as a complex quantity,[8] the real component being a hyperbolic angle, expressible in hyperbolic radians, and the imaginary, or j-component, a circular angle expressed in circular radians. This j-component measures the wave phase-length of the line at the frequency considered. In this case, the wave-length of the whole line AB is shown to be 12.723 circular radians. It is convenient for many purposes, however, to divide the j-component by $\pi/2$, or 1.5708, in order

8. "The Application of Hyperbolic Functions to Electrical Engineering Problems," by A. E. Kennelly, University of London Press, 1912, Chap. V.

to reduce this circular angle to quadrant measure. This reduction appears in the fourth column. The whole line AB subtends a complex hyperbolic angle $2.350 + j\,12.723 = 12.94\,\underline{/79.5}$ hyps., of which the j-component is 8.1 in quadrant measure. That is, the wave phase-length of the line is 8.1 quadrants, or a little more than 2 complete revolutions. In other words, the artificial line at this frequency covers a little over 2 complete wave-lengths, and the equivalent smooth line corresponding to the artificial line at junctions, would also cover a little over 2 complete wave-lengths. This hypothetical equivalent smooth line which would conform electrically to the lumpy artificial line at junction points, may be briefly denoted as the *imitated line*.

The fifth column of Table III gives the hyperbolic sine of the angle δ at the respective artificial-line junction points.[9] The potential along the artificial line from junction to junction, and on the imitated line at all points, follows sinh δ in simple proportion. The voltage E' so computed, appears in column 6, starting with $1.00\,\underline{/0°}$ volt at $\sinh\delta = 5.2\,\underline{/9°.2}$, phase angles appearing as degrees and decimals of a degree. Column 7 gives the corresponding observed junction-potential in magnitude and phase with the aid of the potentiometer, taking the initial impressed voltage as $1.00\,\underline{/0°}$ volt. It will be noticed that the agreement between the computed voltage E' and the observed voltage E is satisfactory, the magnitudes usually agree within 5 per cent and the phase within 5 deg. A discrepancy of 5 deg. may seem considerable in itself, but the total change of voltage phase along the line is about 720 deg.

Column 8 gives the hyperbolic cosines of the mid-section angles. It has been shown[10] that the current in any Π-section of an artificial line, when multiplied by the hyp. cosine of a semi-section, agrees with the current on the imitated line at the corresponding point; also that the current at any point of a smooth line is directly proportional to the hyp. cosine of the angle from the distant end. Column 9 gives in this way the computed current at the points on the imitated line corresponding to mid-

9. Tables of complex hyperbolic functions expressed as sinh, cosh, or tanh of $(x + jq)$ from $x = 0$ to $x = 10$, and $q = 0$ to $q = \infty$, by steps in each of 0.05, have been computed, and are in course of publication by the Harvard University Press, together with large-scale interpolation charts.

10. "The Distribution of Voltage and Current over Artificial Lines in the Steady State," by A. E. Kennelly, *Electrical World*, New York, August 10, 1912.

TABLE III

LINE GROUNDED AT B

Point	Distance from B km.	Hyperbolic angle from B: $\delta = x + jy$ hyps. radians	Hyperbolic angle from B: quadrants	sinh δ	Voltage along line: E′ computed volts	Voltage along line: E observed volts	cosh δ	Current strength along line: I′ computed	Current strength along line: I observed milliamperes	Current strength along line: I cosh δ reduced
A	800	2.350 + j12.723	j8 .10	5.20 /9°.2	1.000/0°	1.000/0°	5.288/8°.8	2.227/12°	2.227/12°	2.227 /12°
I	760	2.233 + j12.087	j7.695				4.710\27°.1	1.984\23°.9	2.454\32°	1.995 \27°
1	720	2.115 + j11.451	j7.290	4.165\64°.2	0.801\73°.4	0.797\84°				
II	680	1.998 + j10.815	j6.805				3.632\108°.1	1.531\104°.9	1.953\114°.2	1.588\109°.2
2	640	1.880 + j10.179	j6.480	3.275\134°.6	0.630\143°.8	0.625\152°.3				
III	600	1.763 + j 9.543	j6.075				2.964\173°.6	1.247\170°.4	1.538\180°	1.250\175°
3	560	1.645 + j 8.906	j5.670	2.545\212°.3	0.490\221°.5	0.482\228.2				
IV	520	1.528 + j 8.270	j5.265				2.181\244°	0.919\240°.8	1.150\255°.7	0.935\250°.7
4	480	1.410 + j 7.634	j4.860	2.158\281°.8	0.415\290°.7	0.427\302°				
V	440	1.293 + j 6.998	j4.455				1.847\323°.5	0.778\320°.3	0.923\332°.2	0.750\327°.2
5	400	1.175 + j 6.362	j4.050	1.466/5°.4	0.282\3°.8	0.286\5°				
VI	360	1.058 + j 5.726	j3.645				1.525\25°.9	0.642\22°.7	0.780\34°	0.634\29°
6	320	0.940 + j 5.089	j3.240	1.428\73°.5	0.275\82°.7	0.271\92°.3				
VII	280	0.823 + j 4.453	j2.835				0.955\111°.4	0.402\108°.2	0.510\121°.2	0.415\116°.2
7	240	0.705 + j 3.817	j2.430	0.994\128°.5	0.191\135°.7	0.199\143°				
VIII	200	0.588 + j 3.181	j2.025				1.177\178°.7	0.496\175°.5	0.618\185°	0.502\180°
8	160	0.470 + j 2.545	j1.620	0.749\237°.9	0.144\247°.1	0.140\253°.7				
IX	120	0.353 + j 1.909	j1.215				0.484\224°.8	0.204\221°.6	0.279\226°	0.227\221°
9	80	0.235 + j 1.272	j0.810	0.982\374°.2	0.1889\283°.4	0.1965\294°				
X	40	0.118 + j 0.636	j0.405				0.813\355°	0.342\351°.8	0.439\0°	0.356\355°
B	0	0. + j 0	j0.	0.	0.	0.	1.000/0°	0.421\356°.8	0.439\0°	0.439\360°

section points on the artificial line. Column 10 gives the observed section current I, and the last column gives $I \cosh u$, $\cosh u$ being, for this line, the vector $0.813 \angle 5°$. The agreement should be exact, theoretically speaking, between the entries in columns 9 and 11 under I' and $I \cosh u$ respectively. It is not exact in the case considered, but is nevertheless satisfactory.

Table IV gives the corresponding computed and observed potentials and currents with the distant end free. Here the free end of the line constitutes an initial line angle of $j\,\pi/2$ or $j\,1.5708$ radians at B, or just 1 quadrant, which has been added

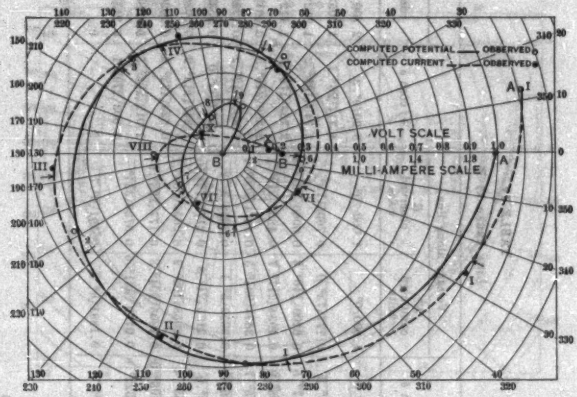


FIG. 3—LINE GROUNDED AT DISTANT END. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

to all the angles. The voltages follow the sines, and the currents the cosines, of the angles from point to point. The agreement is again satisfactory, although by no means exact, between E' and E, also between I' and $I \cosh u$.

Table V gives a similar comparison of computed and observed potentials and currents for the case of the line grounded at the distant end through a subscriber's set which offered an impedance of $1570 \angle 70°$ ohms, and which therefore subtended a terminal angle of $\tanh^{-1}\left(\frac{1570 \angle 70°}{465 \angle 11°}\right) = 0.043 + j\,1.285$ hyp.; or, with

TABLE IV

Line Freed at B

Point	Distance from B km.	Hyperbolic angle from B: $\delta = x + jy$ hyps.	Hyperbolic angle from B: $\delta = x + jy$ radians	Hyperbolic angle from B: $\delta = x + jy$ quadrants	$-j \sinh \delta$	Voltage along line: E' computed volts	Voltage along line: E observed volts	$-j \cosh \delta$	Current strength along line: I' computed	Current strength along line: I observed milliamperes	Current strength along line: $I \cosh x$ reduced
A	800	2.350 + j14.294	j9.10	5.288/8°.8	1.000/0°	1.000 /0°		5.20/9°.2	2.100 /13°	2.100/13°	2.100/13°
I	760	2.233 + j13.658	j8.695					4.717\26°.7	1.905\22°.9	2.286\31°	1.858\26°
1	720	2.115 + j13.022	j8.290	4.109\64°.2	0.777\73°.0	0.7605\78°					
II	680	1.998 + j12.386	j7.805					3.743\107°.2	1.512\103°.4	1.917\109°.9	1.559\104°.0
2	640	1.880 + j11.750	j7.480	3.283\137°.5	0.6209\146°.3	0.6060\151°.8					
III	600	1.763 + j11.114	j7.075					2.753\176°.6	1.112\172°.8	1.385\176°.2	1.126\171°.2
3	560	1.645 + j10.477	j6.670	2.609\208°.9	0.4934\217°.7	0.4857\219°.1					
IV	520	1.528 + j 9.841	j6.265					2.380\248°.5	0.9613\244°.7	1.183\255°.8	0.962\250°.8
4	480	1.410 + j 9.205	j5.860	1.950\285°.7	0.3688\294°.5	0.3671\300°.1					
V	440	1.293 + j 8.569	j5.455					1.806\312°.2	0.7294\308°.4	0.8943\320°.0	0.727\315°
5	400	1.175 + j 7.933	j5.050	1.773\356°.3	0.3353\5°.1	0.3358\3°.2					
VI	360	1.058 + j 7.297	j4.645					1.370\38°.0	0.5533\34°.2	0.6874\40°.2	0.559\35°.2
6	320	0.940 + j 6.660	j4.240	1.129\63°.0	0.2135\71°.8	0.2175\72°.9					
VII	280	0.823 + j 6.024	j3.835					1.247\113°.2	0.5036\109°.4	0.6942\108°	0.564\103°
7	240	0.705 + j 5.388	j3.430	1.088\153°.4	0.2058\162°.2	0.2052\164°.1					
VIII	200	0.588 + j 4.752	j3.025					0.624\172°.8	0.2520\169°.0	0.3172\177°.1	0.258\172°.1
8	160	0.470 + j 4.116	j2.620	0.9547\196°.0	0.1805\204°.8	0.177\203°.9					
IX	120	0.353 + j 3.480	j2.215					1.012\263°.5	0.4088\259°.7	0.528\260°.5	0.429\264°.5
9	80	0.235 + j 2.843	j1.810	0.3854\322°.8	0.0729\331°.6	0.0726\331°					
X	40	0.118 + j 2.207	j1.405					0.603\279°.1	0.2435\275°.3	0.303\282°.2	0.246\277°.2
B	0	0. + j 1.571	j1.000	1.000\0°	0.1891\8°.8	0.191\8°.7		0.	0.	0.	0.

the j-component in quadrant measure, $0.043 + j0.818$, the surge-impedance of the artificial line being $465 \angle 11°$ ohms. All the angles of Table III are here increased by these amounts. The potentials are then simply proportional to $\sinh \delta$, and the currents to $\cosh \delta$, as before. A satisfactory agreement is found between the columns under E' and E; and also under I' and $I \cosh u$.

Figs. 3, 4 and 5 are vector charts, corresponding respectively to Tables III, IV and V. Referring to Fig. 3, with Table III, it will be seen that the potential at A commences at $1.0 \angle 0°$ volt. The continuous curve then traces the hyperbolic-sine locus of

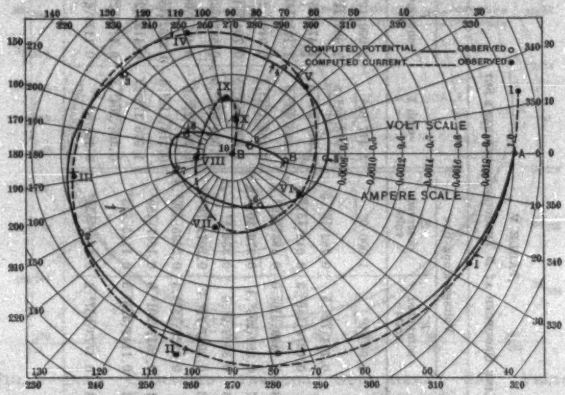


FIG. 4—LINE FREED AT DISTANT END. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

potential along the imitated line, both in magnitude and phase, it being understood that equal distances in kilometers do not generally correspond to equal phase differences. The arrowheads, intersecting the potential curve, mark the points on the imitated line at 80-km. intervals, corresponding to the junctions of the artificial-line sections. A small circle marks the corresponding vector potential observed. The arrowheads and circles should coincide, theoretically. Similarly, the broken line traces the computed hyperbolic-cosine locus of the vector-current along the imitated line, arrowheads indicating points at 80-km. intervals corresponding to mid-sections on the artificial line.

TABLE V

Line Grounded at B Through Subscriber's Set

Point	Distance from B km.	Hyperbolic angle from B: $\delta = x + jy$ hyp. radians	Hyperbolic angle from B: $\delta = x + jy$ quadrants	sinh δ	Voltage along line: E' computed volts	Voltage along line: E observed volts	cosh δ	Current strength along line: I' computed	Current strength along line: I observed milliamperes	Current strength along line: I cosh u reduced
A	800	$2.393 + j14.008$	$j8.918$	$5.520/82°.2$	$1.000/0°$	$1.000/0°$	$5.477/81°$	$2.099/12°$	$2.099/12°$	$2.099/12°$
I	760	$2.276 + j13.372$	$j8.513$	$4.272/9°.7$	$0.774\backslash72°.5$	$0.762\backslash78°.6$	$4.976/44°.5$	$1.907\backslash24°.5$	$2.362\backslash31°$	$1.920\backslash26°$
1	720	$2.158 + j12.736$	$j8.108$		$0.6274\backslash146°.3$	$0.616\backslash151°.6$	$3.846\backslash26°.5$	$1.474\backslash95°.5$	$1.935\backslash108°.8$	$1.573\backslash103°.8$
II	680	$2.041 + j12.100$	$j7.703$				$2.965\backslash99°.9$	$1.136\backslash168°.9$	$1.427\backslash176°.7$	$1.160\backslash171°.7$
2	640	$1.923 + j11.464$	$j7.298$	$3.463\backslash64°.1$						
III	600	$1.806 + j10.828$	$j6.893$				$2.469\backslash171°.7$	$0.9462\backslash240°.7$	$1.218\backslash254.6°$	$0.990\backslash249°.6$
3	560	$1.688 + j10.191$	$j6.488$	$2.704\backslash133°.8$	$0.4899\backslash216°.0$	$0.483\backslash219°.1$				
IV	520	$1.571 + j9.555$	$j6.083$				$1.837\backslash243°.5$	$0.704\backslash312°.5$	$0.851\backslash320°.7$	$0.692\backslash315°.7$
4	480	$1.453 + j8.919$	$j5.678$	$2.077\backslash211°$	$0.382\backslash293°.4$	$0.379\backslash301°.8$				
V	440	$1.336 + j8.283$	$j5.273$				$1.534\backslash324°.9$	$0.5879\backslash33°.0$	$0.7386\backslash40°.1$	$0.601\backslash35°.1$
5	400	$1.218 + j7.647$	$j4.868$	$1.826\backslash280°.6$	$0.3308\backslash2°.8$	$0.334\backslash1°$				
VI	360	$1.101 + j7.011$	$j4.463$				$1.299\backslash27°.9$	$0.4978\backslash96°.9$	$0.6602\backslash103°.5$	$0.537\backslash98°.5$
6	320	$0.983 + j6.374$	$j4.058$	$1.152\backslash353°.5$	$0.2087\backslash75°.7$	$0.2071\backslash78°.1$				
VII	280	$0.866 + j5.738$	$j3.653$				$0.718\backslash113°.3$	$0.2752\backslash182°.8$	$0.3481\backslash188°.2$	$0.283\backslash183°.2$
7	240	$0.748 + j5.102$	$j3.248$	$1.236\backslash75°.1$	$0.2239\backslash157°.3$	$0.2295\backslash159°.8$				
III	200	$0.631 + j4.436$	$j2.843$				$1.078\backslash175°.7$	$0.4131\backslash247°.7$	$0.5548\backslash258°$	$0.443\backslash253°$
8	160	$0.513 + j3.830$	$j2.438$	$0.834\backslash110°.4$	$0.1511\backslash201°.6$	$0.1537\backslash199°$				
IX	120	$0.396 + j3.194$	$j2.033$				$0.369\backslash204°.8$	$0.1414\backslash273°.8$	$0.1868\backslash274°.3$	$0.152\backslash269.3°$
9	80	$0.278 + j2.557$	$j1.628$	$0.631\backslash243°.3$	$0.1143\backslash325°.5$	$0.1115\backslash333°$				
X	40	$0.161 + j1.921$	$j1.223$				$0.293/8°$	$0.1123\backslash61°$	$0.115\backslash62°$	$0.115\backslash62°$
	0	$0.043 + j1.285$	$j0.818$	$0.979\backslash275°.3$	$0.1773\backslash357°.5$	$0.1828\backslash352°$				

The black dot circles mark the reduced current measurements. These arrowheads and black dots should also coincide, according to theory.

It will be seen that the current leads the impressed e.m.f. at *A* by 12 deg. As we advance down the line, both potential and current fall behind the phase of the impressed terminal e.m.f. The change in phase is about 720 degrees for potential, and 732 degrees for current; or about 0.9 deg. per km.

In the case of Fig. 4 and Table IV, it will be noted that freeing the line at the distant end, slightly diminishes the current at

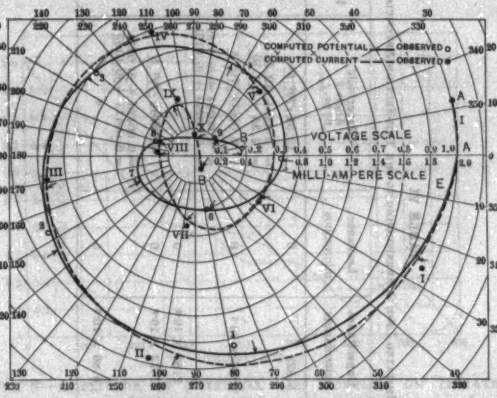


FIG. 5—LINE GROUNDED THROUGH SUBSCRIBER'S SET. VECTOR DIAGRAM OF VOLTAGE AND CURRENT

the sending end, without materially affecting its phase. Towards the distant end of the line, the magnitude and phase of the current are, of course, increasingly affected.

Figs. 6, 7 and 8 show the computed magnitudes of voltage and current along the imitated line without respect to phase. The broken dotted straight lines indicate the correspondingly computed magnitudes of voltage along the artificial line, on the assumption that the resistance and inductance are uniformly distributed in each section coil; also that the capacitance between the coil windings can be ignored. The voltages at

TABLE VI

ELECTRICAL CONSTANTS OF IMITATED LINE CORRESPONDING TO THE TEN-SECTION ARTIFICIAL LINE AT 760 ~.

	Resistance at 20° cent. ohms	Inductance henrys	Capacitance microfarads	Leakance micromhos	Hyperbolic Angle θ hyps. $\underline{/}$	Surge Impedance z_0 ohms $\underline{/}$	Remarks
Line (800 km.)...	2205	1.173	5.823	0	$12.94\ \underline{/79^\circ.5}$ $= 2.35 + j12.72$ $= 2.35 + j\ \underline{8.10}$	$465\ \underline{\backslash 11^\circ}$	The imitated line corresponds approximately to one of a pair of No. 9 A. W. G. copper wires, diameter 2.9 mm. 0.114 in. separated in air to a distance of 1000 diameters or 2.9 meters.
Per wire-km.....	2.756	1.463×10^{-3}	7.28×10^{-3}	0	$0.01618\ \underline{/79^\circ.5}$ $= 0.00294 + j0.0159$ $= 0.00294 + j\underline{0.0101}$	$465\ \underline{\backslash 11^\circ}$	Underscored imaginary quantities are in quadrant measure.
Per loop-km.....	5.512	2.926×10^{-3}	3.64×10^{-3}	0	*	$930\ \underline{\backslash 11^\circ}$	
Per wire-mile....	4.44	2.35×10^{-3}	11.72×10^{-3}	0	$0.02604\ \underline{/79^\circ.5}$ $= 0.00473 + j0.0256$ $= 0.00473 + j\underline{0.0163}$	$465\ \underline{\backslash 11^\circ}$	
Per loop-mile....	8.88	4.70×10^{-3}	5.86×10^{-3}	0	*	$930\ \underline{\backslash 11^\circ}$	

section-junctions and line-terminals then agree with those of the imitated line at such points. The current strengths in the artificial line would, if shown on the diagram, be constant in each section, and would be represented by horizontal straight lines, broken by vertical descents at leak-junctions. When multiplied by cosh u, these currents would agree with the imitated line currents at mid-section points.

In the case of Fig. 6 and Table VI, the current strength arriving at the subscriber's set is $0.115 \angle 62°$ milliampere. The potential difference at the terminals of the receiving telephone T was $0.040 \angle 230°$ volt, and taking the impedance of this

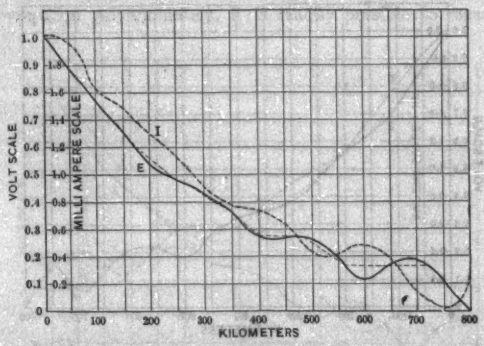


FIG. 6—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, GROUNDED AT DISTANT END

instrument at $260 \angle 40°$ ohms, as found by subsequent experiments, the current received in the instrument would be $0.040 \angle 230° / 260 \angle 40° = 0.154 \angle 270°$ milliampere. This current gave rise to a loud musical note in the receiver.

EQUIVALENT CIRCUITS OF ARTIFICIAL AND IMITATED LINES

Table VII contains data concerning the artificial line taken as a whole, and also concerning the imitated line, its external counterpart. Figs. 9 and 10 show the nominal and equivalent circuits of these lines. In Fig. 9, the nominal Π, $A''B''$, contains an architrave impedance $2202 + j5599$ ohms, and the imitated

line would contain this impedance at the testing frequency. In each of the two terminal leaks there would be 0.01391 $\underline{/90°.5}$ mho, corresponding to 2.913 microfarads of total distributed capacity. Similarly, the nominal T, $A'B'$, contains in its arms a total of $2202 + j5599$ ohms, and in its single leak 0.02782 $\underline{/90°.5}$ mho.

Fig. 10 shows the equivalent Π, $A''B''$, of three simple impedances which would externally replace either the whole artificial line, or the imitated line. The architrave impedance is $2417 - j\,76$ ohms. Each pillar leak has an admittance of $(1.737 + j\,0.391)\,10^{-3}$ mho. If we apply one volt to the terminal A'', then by

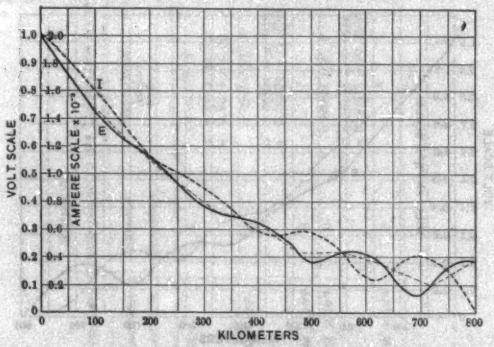


FIG. 7—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, FREED AT DISTANT END

freeing, grounding, or connecting-to-instrument the end B'', we obtain there the corresponding terminal voltages and currents observed and computed for the artificial line. That is, the current, voltage, and power will be the same at the terminals A'', B'', as at the terminals A and B respectively of the artificial line, or of the imitated smooth line, under like conditions of operation. Similarly, the equivalent T in Fig. 10, has $380 - j62.2$ ohms in each arm, and 11.19×10^{-3} $\underline{/20°.2}$ mho in its leak.

Free and Ground Impedance Tests of Artificial Line. Table VIII collects a set of measurements on the impedance of different lengths; *i.e.*, different numbers of sections in the artificial

line, commencing with one section and ending with 10 sections. Each impedance is the ratio of the terminal impressed voltage to the entering current strength. It will be seen that although the impedances, free and grounded at the far end, vary greatly as the number of sections is changed, yet their product is constant within errors of observation, and its square root, their geometric mean, is the constant surge-impedance of the line. The square root of the ratio of the two impedances also measures the tangent of the hyperbolic angle subtended by the line.

Precision of Measurements. Owing to the great sensitiveness of vibration galvanometers, it is readily possible to measure,

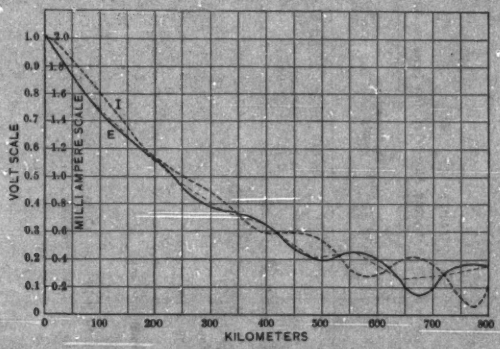


FIG. 8—AMPLITUDE OF POTENTIAL AND CURRENT ON IMITATED SMOOTH LINE, AND AMPLITUDE OF POTENTIAL ON ARTIFICIAL LINE, GROUNDED THROUGH SUBSCRIBER'S SET AT DISTANT END.

as above described, the potential and current along an artificial line, fairly representing 800 km. (500 miles) of aerial telephone line, without using more than 1.75 volts at the sending end per wire, or 3.5 volts per loop on the metallic circuit basis. The precision of the measurements, however, is not so great at the telephonic frequency of 760 ~, as at the lighting frequency of 60 ~. This relative falling off in precision may be attributed to several causes: namely, first, capacity effects in apparatus and leads not noticeable at low frequencies; second, want of practise with the technique of the method and apparatus at the higher frequency; third, stray magnetic fields in coils and galvan-

TABLE VII

ELECTRICAL CONSTANTS FOR BOTH THE ARTIFICIAL AND IMITATED LINES

Angle θ hyps. $\angle$	Surge impedance z_0 ohms $\angle$	sinh θ	tanh $\theta/2$	Semi-section angle u	Correcting factors		
					cosh u	$\frac{\sinh \theta}{\theta}$	$\frac{\tanh (\theta/2)}{\theta/2}$
$12.94\angle 79°.5$	$465\angle 11°$	$5.2\angle 9°.2$	$0.8277\angle 1°.7$	$0.647\angle 79°.5$	$0.813\angle 5°$	$0.4018\angle 70°.3$	$0.1279\angle 77°.8$
$= 2.35 + j12.72$				$0.1175 + j0.636$			
$= 2.35 + j\,8.10$				$0.1175 + j0.405$			

Equivalent Π

Architrave impedance	$z_0 \sinh \theta$	$= 2418\angle 1.8°$ ohms.
		$= 2417 - j76$ ohms.
Pillar leak admittance	$1/\{z_0 \tanh (\theta/2)\}$	$= 1.78 \times 10^{-3}\angle 12°.7$

Equivalent T

Arm impedance	$z_0 \tanh (\theta/2)$	$= 385\angle 9.3°$ ohms.
		$= 380 - j62.2$ ohms.
Staff leak admittance	$1/(z_0 \sinh \theta)$	$= 11.19 \times 10^{-3}\angle 20°.2$ mho.
		$= (10.5 + j3.862)\,10^{-3}$ mho.

ometer leads, a very small flux alternating at the higher frequency, and linked with the galvanometer circuit, being able to set up a very appreciable e.m.f.; fourth, irregularities in the section condensers at the higher frequency (if the condensers along the artificial line are adjusted to equality at a low frequency they may readily show differences as well as diminutions in capacity at the higher frequency); fifth, deviation of the wave form of impressed e.m.f. from the sinusoidal, or the presence of harmonics. This affects the split-phase balance, and phase measurements. The vibration galvanometer may be broadly

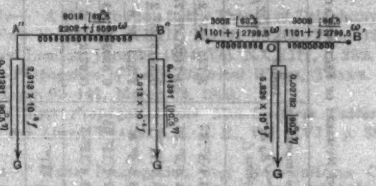


FIG. 9—NOMINAL Π AND T OF THE IMITATED LINE

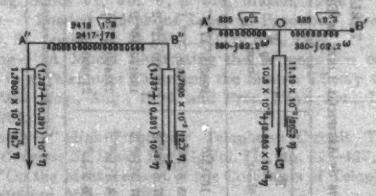


FIG. 10—EQUIVALENT Π AND T OF ARTIFICIAL AND IMITATED LINES

considered as responding only to the fundamental frequency, the harmonics being independent of it, and unable to affect it. Nevertheless, the presence of the harmonics is able to produce some disturbance of the zero, and thus may have some small influence on the measurements.

By practise, and with further experience, some of the abovementioned disturbing sources may be reduced, and the precision of measurement increased. Nevertheless, the precision attained in the results here reported will doubtless be considered as satisfactorily sustaining the theory of such telephone-line transmission, at a single telephonic frequency, in the steady

TABLE VIII

IMPEDANCE TESTS OF ARTIFICIAL LINES OF DIFFERENT NUMBERS OF SECTIONS AT 760 ~

No. of sections	Impedance: Grounded Z_g ohms $\angle$	Impedance: Freed Z_f ohms $\angle$	$Z_g Z_f$ ohm² $\angle$	Surge impedance $Z_s = \sqrt{Z_g Z_f}$ ohms $\angle$	$\tanh \theta = \sqrt{Z_g/Z_f}$	θ	2α mean section angle
1	1244/38°.4	167\56°	208300\17.6	456.4\8°.8	2.725 /47°.2	0.246 + j1.342	0.246 + j1.342
2	346.4\47°.3	623.8/28°.2	216100\19°.1	464.9\9°.55	0.7452\37°.75	0.497 + j2.583	0.249 + j1.292
3	441.3/14°.1	497.8\36°.3	219700\22°.2	468.7\11°.1	0.9415/25°.2	0.747 + j3.855	0.249 + j1.285
4	588\2°.6	337.5\16°.6	198470\19°.2	445.5\9°.6	1.320 /7°.0	0.940 + j4.510	0.235 + j1.128
5	387.7\10°.6	576.1\13°.5	223400\24°.1	472.7\12°.05	0.8203/1°.45	1.157 + j0.346	0.231 + j1.269
10	449.0\12°.0	476.2\13°	213800\25°	462.4\12°.5	0.9712/0°.5	2.35 + j12.72	0.235 + j1.272
			Accepted mean values	465.\11°			0.235 + j1.272

state. A great variety of telephonic tests and measurements can be made on such an artificial line under different terminal conditions, and with different receiving instruments. Such an artificial telephone line has great practical value for the telephone engineer, the investigator and the student.

BIBLIOGRAPHY

GIVING AN INCOMPLETE LIST OF PAPERS REFERRING TO MEASUREMENTS ON ARTIFICIAL TELEPHONE LINES AND ALLIED TOPICS

A. E. Kennelly—"A Contribution to the Theory of Telephony," *Electrical World*, New York, Vol. XXIII, No. 7, p. 208, Feb., 1894, and *The Electrician*, London, June 29, 1894, Vol. XXXIII, p. 232.

M. I. Pupin—*Propagation of Long Electrical Waves*, TRANS. A. I. E. E., Vol. XVI, pp. 93–142, March 22, 1899.

M. I. Pupin—*Wave Propagation over Non-Uniform Cables and Long-Distance Air Lines*, TRANS. A. I. E. E., Vol. XVII, p. 385, May 18, 1900.

M. I. Pupin—"Wave Propagation over Non-Uniform Conductors," *Trans. Am. Math. Soc.*, Vol. I, No. 3, pp. 259–286, July, 1900.

G. A. Campbell—"On Loaded Lines in Telephonic Transmissions," Phil. Mag. Series VI, Vol. V, p. 313, March, 1903.

H. V. Hayes—"Loaded Telephone Lines in Practice," *Proc. Int. Elec. Congress*, St. Louis, Sec. G., Vol. III, p. 638, 1904.

J. A. Fleming—"A Model Illustrating the Propagation of a Periodic Current in a Telephone Cable and the Simple Theory of its Operation," *Phil. Mag.*, Aug., 1904, and *Proc. Phys. Soc.*, London, Vol. XIX, 1904.

A. E. Kennelly—"High-Frequency Telephone Circuit Tests," *Proc. Int. El. Congress St. Louis*, Sec. G, Vol. III, pp. 414–437, 1904.

Béla Gáti—"On the Measurement of the Constants of Telephone Lines," *The Electrician*, Nov. 2, 1906.

B. S. Cohen and G. M. Shepherd—"Telephonic Transmission Measurements," *Journ. of Proc. Inst. El. Engrs.*, London, Vol. XXXIX, p. 503, 1907.

Béla Gáti—"Uber die Anwendung hyperbolischer Functionen auf weite Entfernungen wirkenden Telegraphen- und Telephonenströmen." *Electrotechnik und Maschinenbau*, Vol. 33, 1910.

K. W. Wagner—"Uber die Frequenz der Fernsprechströme," *Elektrotechnische Zeitschrift*, 1910.

J. A. Fleming—"The Propagation of Electrical Currents in Telephone and Telegraph Conductors," Constable & Co., London, May, 1911.

F. Breisig—"Uber die Energieverteilung in Fernsprechkreisen," *Elektrotechnische Zeitschrift*, June, 1911, Vol. XXIII, pp. 558–561, Vol. XXIV, pp. 590–593.

K. W. Wagner—"Elecktromagnetische Ausgleichsvorgänge in Freileitungen und Kabeln," *Elektrotechnische Zeitschrift*, 1911, pp. 899, 928, 947.

A. E. Kennelly—"The Application of Hyperbolic Functions to Electrical Engineering Problems," The University of London Press, 1912.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 24, 1913.

Copyright, 1913. By A. I. E. E.

AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION

BY H. M. FRIENDLY AND A. E. BURNS

In designing the equipment used by the Northwestern Long Distance Telephone Company, operating a toll system connecting independent local telephone exchanges in Western Oregon and Western Washington, the first consideration was to improve the traffic capacity of operators, lines and equipment. Incidental to this was the desire to render the work of the operator more mechanical, so that the personal equation would be eliminated as far as possible in the handling of switching equipment. To this end, somewhat radical and seemingly complicated electrical circuits were resorted to in accomplishing complete, positive lamp supervision, and in meeting various traffic requirements and expedients, but as long as such departures from common practise meant simpler operating, more rapid switching, or increased transmission efficiency, all consistent with reliability and normal maintenance, the means were considered as fully justified.

The fact being that the Northwestern Long Distance Telephone Company has no direct authority over its connecting companies, the inability to enforce discipline and strict traffic rules over foreign operators had to be taken into consideration, and every possible step employed to improve and quicken the service in order to counteract this deficiency, competition for business being very keen.

It will be observed that the equipment on the toll switchboards, proper, is free from special, irregular or complicated devices that require great care and special instruction for proper operation—that the circuits are uniform at all operators' positions—

that the minimum of apparatus subject to adjustment is employed in the switchboard; such apparatus, wired in sets, being placed in the wirechief's room, or in any other place where it may be convenient for inspection and repairs, without in any way interfering with or annoying operators at work. Further, the apparatus-sets have been mounted in detachable units, thus allowing a complete change of the character or type of equipment associated with any line without altering or mutilating wiring in the apparatus-set. Each detachable apparatus-set consists of a frame ¾ by ¾ by ¾ in. (3.1 by 19 by 19 mm.) angle iron, bent to form three sides of a rectangle 5 by 16 in. (12.7 by 40.5 cm.), the top being left open. A piece of 24-gage sheet iron is riveted to the back to form a dust-proof, induction-proof case, and a close-fitting sheet iron detachable cover is provided for the front, it being found that where the apparatus sets are mounted close together (6-in. or 15-cm. centers) without cross-talk protection, when relays of one set were being operated, induced clicking noises could be heard on the lines associated with the nearby apparatus sets. The top of each apparatus-set frame is closed by a piece of the same angle iron, bent and pivoted to form a sort of rocking switch carrying eleven insulated points used as terminals; these points are made to engage with insulated companion springs or clips on the stationary rack, the latter being of 3/16 by 2 by 2-in. (4.7 by 50.8 by 50.8 mm.) angle iron. All external wires are brought to the rack clips permanently; thus to remove an apparatus set, and substitute another, it is only necessary to disengage the clips, unhook the set from the rack, place the desired set on the rack and tilt the rocking switch so its points engage their companion rack clips. All wiring of the sets is brought out to the rocking switch, the wiring having extra heavy braided insulation, and so disposed loosely in the set that it is not injured by the small hinge movement of the rocking switch in cutting the set in or out of service. The detachable feature of the apparatus-sets allows such equipment at distant offices to be removed and sent to the shop for repairs or alterations in specially designed shipping boxes, avoiding the necessity of sending out a high-priced man and paying the incidental cost of transportation, etc. The expense of one such trip alone to some of the distant offices would more than pay the cost of a duplicate set to be kept for such emergencies. An operator, or any inexperienced person, can easily effect a change of sets, place the displaced set in the special box and express it to the shop.

The relays used in the apparatus sets are mostly of the automatic vertical type. This type was chosen because of its adaptability, almost any circuit combination desired being possible by merely assembling the proper springs and insulating bushings. The contacts can be given any reasonable degree of tension or pressure, and the slight sliding movement due to construction tends to keep the contact surfaces bright and free from dust. The margin of adjustment in this type of relay is also very wide, and all parts are easy of access for inspection and maintenance. These relays are mounted upon angle-iron shelves, pivoted in the apparatus-set frame in a manner similar to the switch at the top, allowing all the wiring and relays to be tilted out, inspected and repaired without removing them or mutilating the wiring. A gravity-catch locks the relay mount in place when tilted back into normal position. The repeating coils, retardation coils, condensers, etc., associated with the apparatus sets are mounted on the back thereof, since there are no moving parts to inspect or adjust.

Another type of relay that has proved its usefulness and reliability is a polarized relay designed expressly on the plan of a polarized ringer, and which is compact and extremely sensitive, though capable of withstanding abnormal currents without impairing its adjustment—such as 20-cycle ringing power. This relay is also mounted as a part of the apparatus-set, on a pivoted shelf, when the equipment comprises such a relay.

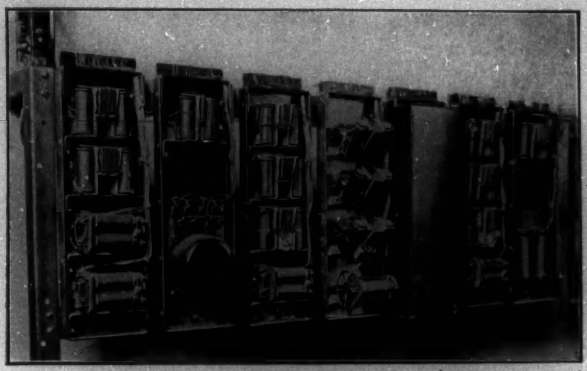
The apparatus sets are secured to the rack by slots which slip over the heads of round-head machine screws on the rack angle iron, the slots being enlarged at the bottom to take the heads of the screws.

One of the first conditions to be surmounted was in the territory between Portland and Tacoma, a distance of 145 miles (233 km.). From Portland north to Centralia, a distance of 95 miles (152 km.), is a No. 10 B. & S. copper circuit, used as a way-line on which are ten stations and offices, each with a 1600-ohm signal (switchboard drops and bells having the same type of movement) having a two-microfarad condenser in series therewith (this latter provision is carried throughout the entire system to facilitate line testing and fault location). From Chehalis, 4 miles (6.4 km.) south of Centralia, to Tacoma, a distance of 50 miles (80 km.), is a similar way-line on which are ten stations. Thus the way-lines lap for a distance of 4 miles (6.4 km.) between Centralia and Chehalis. This lapping was done because these towns are the largest between Portland and Tacoma, and

incidentally are about equal in importance from a traffic standpoint from both directions. The lapping of the circuits obviates delays such as would ensue if intermediate switching had to be resorted to. For normal switching between Portland and Tacoma, and Portland and Seattle, the latter 40 miles (64 km.) north of Tacoma, through trunk lines were provided. However, it is often desired to press into requisition the two way-lines above mentioned for Portland-Tacoma traffic. Any intermediate traffic is handled over these way-lines, excepting rush calls when the way-lines are busy. Two No. 10 B. & S. copper way-lines are provided in addition to the above, between Portland and Castlerock, a distance of 62 miles (99 km.) north. These lines are equipped for calling direct into the local automatic exchange at Portland. The methods used will be explained further on.

Delays in the establishing of, and in the taking down of switching connections manually at Centralia or Chehalis for such through traffic led to the equipment of the way-lines for performing this function of interconnection and disconnection remotely, from either Portland or Tacoma, under the instant automatic control of the operators—day or night. The electrical circuit accomplishing this is shown in Figs. 1 and 2, and later described. The operating specifications of the through switching circuit are as follows:

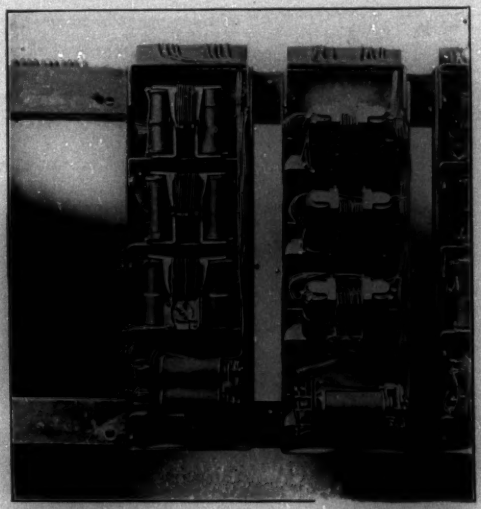
The lines are normally used as way-lines without any restrictions whatsoever. Assuming that Portland desires to communicate with Tacoma—bear in mind that the switching and line equipments at both Portland and Tacoma are identical (excepting that battery on relay *D*, Fig. 1, is reversed at Tacoma as indicated in the diagram), and similarly operated, and that the equipment at Centralia for effecting the interconnection (obviously this equipment could have been installed at Chehalis, or even on a pole between the towns, with the same effect) is actuated from either Portland or Tacoma—first the Portland operator ascertains if the Portland-Centralia line is busy by listening-in on the line. If not busy, the operator withdraws the plug from the regular jack and inserts it into the jack following, which may be called the through switching jack; over the latter jack is a number designating the remote line. Inserting the plug into the through switching jack causes the equipment at Centralia to be actuated, connecting the lines together, so that the Portland operator by listening-in can instantly know if the remote line is idle, and that without any disturbance to possible



[FRIENDLY AND BURNS]

VIEW OF PORTION OF RACK SHOWING APPARATUS SETS

No. 4 has relays tilted out for inspection. No. 5 is set with dust-proof cover in place.



[FRIENDLY AND BURNS]

VIEW OF TWO APPARATUS SETS

Set to the left has been removed to show springs at top of rack which engage with points of the rocking switch at top of set.

users on the remote line. If the remote line is found idle, the Portland operator rings Tacoma's signal, or the signal of any office on the remote line, in the usual way, with her regular cord-ringing-keys, no special keys or devices being employed. Since no bell on the near line rings from the through switching jack, the same code of signals has been used on the near and remote lines, so far as was found convenient. Incidentally, the signal showing at Tacoma in the above instance is above the through switching jack, indicating that the signal comes from Portland. The object of this will be shown later. If an intermediate office on the near line desires Tacoma, for instance, such office rings Portland in the usual way and requests Tacoma. The Portland operator, acting as a through operator, removes her plug from the regular jack and inserts it into the adjacent through switching jack, and if the remote line is found idle, signals as above. As no ringing impulses are projected on the near end, from the through switching jack, an operator listening-in at the intermediate office hears no disturbance. When Tacoma answers the signal corresponding to her through switching jack, the Portland operator can leave the line at once, as Tacoma's plug being in the through switching jack, maintains the through connection. If the call cannot be completed at once, Tacoma signals the calling office over her through switching jack when ready; Portland pays no further attention to the call, and makes no note of it, since Tacoma is a checking office. If, however, an intermediate office on the remote line is desired, the Portland operator supervises and checks the call as if it were a through switch made manually at Portland, which, from an operating standpoint, it is. Tacoma in the latter instance would ignore all signals for intermediate stations coming in on the signal associated with her through switching jack, knowing that Portland, a checking office, is supervising such switches, although Tacoma checks all signals for intermediate stations coming in on the regular line signal.

The electrical details are as follows:

1. The Portland operator plugs into the through switching jack, projecting battery current out on the line and operating the relay at Centralia, cutting the lines together.

2. The operator rings on the through switching jack, which operates a relay in the apparatus-set that reverses the battery projected out on the line. This reversed battery operates a polarized relay at Tacoma, and throws 20-cycle ringing power back on the remote line, the relay at Centralia simultaneously

breaking the line connection during the time the current is reversed.

3. When the ringing key is released, the current is restored to the original direction, the relay at Centralia operates, and the through talking circuit is re-established.

4. When the call is completed the operator withdraws her plug, and the lines are restored to their normally separate condition as far as speech is concerned.

Referring to Fig. 1, at the top of this diagram are the eleven

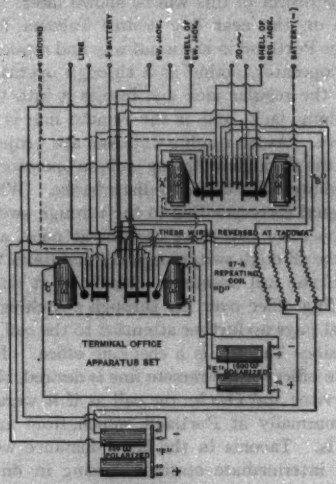


FIG. 1—THROUGH SWITCHING CIRCUIT—TWO-WAY—RING-BACK (SEE FIGS. 2 AND 10)

insulated terminal points carried by the rocking switch at the top of the apparatus set. The companion clips at the top of the rack are connected as shown: No. 1 to main ground; No. 2 and No. 3 to the two wires extending to the line and to the spring jack and drop associated with the line. No. 4 is connected to a set of batteries, in this case dry cells having the negative or zinc pole grounded; No. 5 and No. 6 are connected to the through switching jack and associated signal; No. 7 with the shell or "relay wire" of the through switching jack; No. 8 and No. 9

to 20-cycle ringing power; No. 10 to the shell of the regular line jack; and No. 11 to the main storage battery having the positive pole grounded.

Tracing a particular call, say from Kelso on the Portland way-line to Yelm on the Tacoma way-line, and knowing the modus operandi of the call from the preceding paragraphs, we can follow the action of the relays shown in Figs. 1 and 2. When Kelso rings, the Portland signal associated with the regular line jack is actuated, the jack and drop of the through switching line being unconnected. Portland answers by plugging into the regular line jack, ascertains that Yelm is wanted and changes the cord plug to the through switching jack. The third or shell wire of this plug is grounded, and engaging the shell wire of the through switching jack, throws a ground through point No. 7

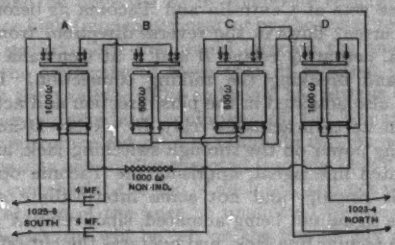


FIG. 2—THROUGH SWITCHING CIRCUIT, CENTRALIA, WASH. (SEE FIGS. 1 AND 10)

of the apparatus set and actuates relays *C* and *D*, Fig. 1, also actuating the cut-off relay associated with the through switching jack. Relay *D* connects the switching jack to the line, and in conjunction with relay *C* projects battery current to the center of relay *F*, where it divides and finds its way through the coils of relay *F*, through two windings of the repeating coil to the line. Following the line to Fig. 2 (Centralia) the battery current flows through the coils of relays *A*, *B*, and *C*, dividing again through the coils of relay *D* to reach the Tacoma way line. The apparatus set at Tacoma is identical with Fig. 1, except, as may be noted, that two of the wires are reversed on relay *D* so that the batteries at Portland and Tacoma will not be opposed when operators have cord plugs in their respective through switching jacks, and the current for ringing control is

necessarily of the opposite polarity. Following the line to Fig. 1 again, this time at Tacoma, the current can be traced through the repeating coils and the coils of relay *F* to ground, whence it returns to the battery at Portland. The current thus established flows on the line from Tacoma to Portland, and relays *B* and *C*, Fig. 2, are wired to operate with this direction of current, connecting the two way-lines together through two four-microfarad condensers. Relay *F* at Tacoma operates to the minus side, and thus produces no effect. When Portland rings, relay *E*, which is bridged across the line, vibrates and thus keeps the contacts practically wide open, the period of contact being of short duration. This allows relay *D*, which has a strong tension, to fall back, and tracing the circuit as before, with relay *C* actuated and relay *D* normal, plus battery current from point No. 4 of the rocking switch is finding its way to the line and through the sets at Centralia and Tacoma as before, but this time the current flows in the reverse direction, from Portland to Tacoma, actuating relays *B* and *C* at Centralia in the plus direction and breaking the talking connection. Relay *F* at Tacoma is also actuated in the plus direction and actuates relay *A* which in its turn actuates relay *B*. Relay *B* impresses 20-cycle ringing power on the through switching jack, and actuates the associated line signal, apprising the Tacoma operator that Portland is ringing, and not some intermediate station, the regular line signal not being actuated, since relay *A* grounds the shell of the regular line jack, and operates the cut-off relay associated with this jack. Relay *B* also impresses 20-cycle ringing power on the primary winding of the repeating coil, and as relay *A* has short-circuited the inner lugs of the secondary winding, 20-cycle ungrounded ringing power is thus projected out on the line. This is important, as the normal ringing power is grounded on one side, and if thrown directly on the line would shunt out a large portion of the operating current, while the alternating current from the live side of the ringing generator would return to ground through the relays of the set, vibrating them and thus breaking up the ringing impulses projected out on the line. Also, grounded ringing power or ringing power subject to grounds from intermediate stations, must be guarded against, otherwise the switching relays at Centralia would operate, cutting the lines together, interfering with service; while the relays at the terminals would operate the switchboard signals and also ring back on the line. This is prevented in two ways.

1. In Fig. 2, the line circuit is carried through the contacts of relays *A* and *B* before reaching the windings of relays *B* and *C*, the switching relays, and any ringing currents on the lines will open these contacts, preventing any ground leakage from operating *B* or *C*.

2. In Fig. 1, relay *A* operates with a ground from relay *F*, and the former in its turn operates relay *B*. The interval of time necessary to accomplish this being comparatively long, ringing impulses of any ordinary frequency will not endure long enough to complete the series of operations. It will be noted, however, that the intermittent ground from the contact of relay *F* is passed on from relay *A* to relay *B*. If the main ground were independently wired to the contacts of each relay it would have the opposite effect, that of producing a steady action of relay *B* by the intermittent action of relay *F*. Of course, this could be obviated as in composite telegraphy, by using a howler or high-frequency ringer, or by the use of repeating coils at these stations, but this would increase the amount of equipment in the aggregate to more than is required in these sets to prevent the trouble. The endeavor has always been to keep unnecessary or avoidable equipment off the line at points where there is no competent man to maintain it. As used, the three apparatus-sets can be disconnected from the lines if desired by pulling the switches at the top of each set, and not only will the normal operation of the lines be unaffected by the change, but no extra apparatus will be left on the line at any of these offices. Conversely, all of these apparatus sets may be regarded as supplementing the regular line equipment, and any facility they may afford in operating may be regarded as that much clear gain.

In the case of the above through switching circuit, ringing power is projected back from the opposite terminal office, since no ringing power is available at Centralia. If such ringing power were available, it could be used to ring in both directions under the control of the terminal offices, in lieu of the method used. The manipulation of the circuit would be the same in either case, as far as the operators are concerned.

A condition in a way similar to the one first described between Portland and Tacoma existed between Portland, and Dallas and Independence via Salem, the latter being 52 miles (83.6 kg.) (No. 10 B. & S. copper) south from Portland, and 15 miles (24 km.) (No. 10 B.w.g. iron) east from Dallas, Independence being

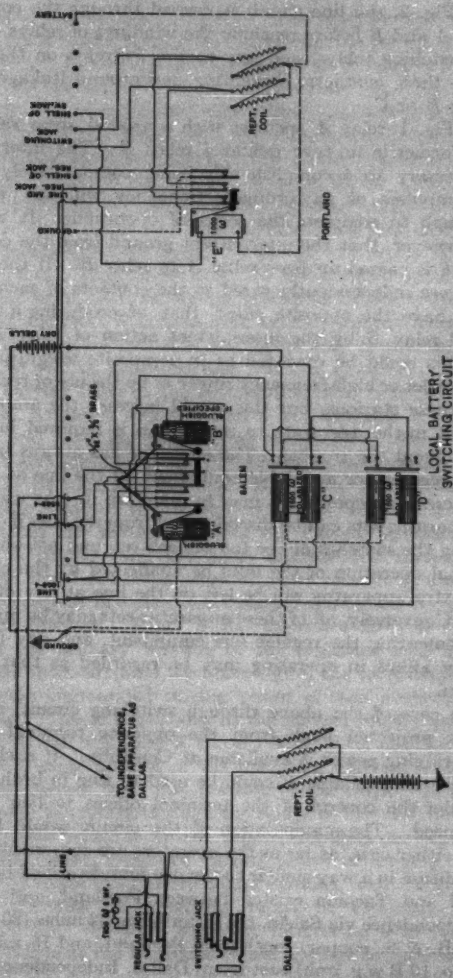


FIG. 3—LOCAL BATTERY THROUGH SWITCHING CIRCUIT (SEE FIG. 10)

on a leg from the latter line. The circuits (see Fig. 3) were somewhat modified by reason of the fact that, due to the small number of stations involved, and the short distance, it is found possible to ring through directly from any office on the line. In this circuit means are provided at each switching station whereby the operator by plugging into the through switching jack causes battery current to be projected out by the line. This battery current serves to operate the through switching relays at Salem which connect the two lines together for talking. Ringing is done directly in the usual manner, and at the termination of the call, the switch is released on the removal of the cord plug from the through switching jack. Two jacks are provided at both Dallas and Independence (see Fig. 3), one the regular line jack, used for normal manual switching, and a through switching jack, provided with extra contacts for connecting the split retardation coil to the line. The center of this coil is connected to battery, the current following the line to Salem and operating the switching relays.

A similar action takes place at Portland, where the retardation coil is connected to the line by means of relay *E*, which is operated from the shell of the through switching jack, projecting current on the line and operating the switching relays at Salem as before. Also, if Dallas, Independence and Portland should all plug into their respective through switching jacks simultaneously, the same effect would take place, the currents from the different sources merely aiding each other after the connection is established at Salem. The operation of the apparatus-set at Salem is on the plan of a mechanically locking relay, which locks the lines together when actuated by relays *C* or *D*, Fig. 3. This relay is operated by six dry cells, and for economy in battery consumption is made to disconnect the local battery after locking mechanically. By this means one set of dry cells can be made to supply the necessary current for a number of months, whereas maintaining the locking action by means of current would shorten the life of cells to a few weeks or possibly days, depending upon the amount of traffic. Either relay *C* or *D* operating to the minus side actuates relay *A*, which when closed actuates relay *B*. Relay *A* is now disconnected from the battery on the back contact of relay *B* and, after a slight pause due to its sluggish properties, falls back. It will be seen from the diagram that this mechanically locks relay *B* in the operated position, disconnecting it electrically,

and it remains in this position as long as relays C and D are energized, holding the lines connected for talking and ringing purposes. When the plug is removed from the through switching jack at the calling office, the current ceases to energize relays C and D; and upon one or both of these relays making contact on the plus side, which is in the normal position of the armatures, current again flows through a make contact of relay B, actuating relay A and unlocking B. Upon relay B returning to its normal position the current in relay A is broken, and it too returns to its normal position, when the set is ready for another switch.

Grounded ringing on one line in the normal position of relays A, B, C, and D will not affect the other line, since relay A must pick up, and after that relay B, and the time necessary to accomplish this is found to exceed the duration of an impulse where the ringing frequency is over fifteen cycles per second.

The mechanism used for locking up relay B in this circuit is capable of wide application. By using a heavy momentary current, it is possible to give the relays a heavy contact tension, thereby reducing the liability to get out of order. The fact that the current is but momentary allows dry cells to be used in stations where a storage battery is not available to operate the relays. This form of locking relay can be used at stations on toll lines where it is desired to have a means of cutting a line in or looping it through a station for testing or switching purposes, and yet due to length of cable or other conditions it is impracticable to allow any permanent legs or loops from the lines, the relays being controlled from contacts on the switching jacks in the station equipment.

Many adaptations other than recounted here may be made—such as through switching between any two of three lines where all terminate at one office; switching from either of two lines to either of two lines, where all four terminate at one office; or switching of three lines in tandem through two through offices, etc. In other words, the apparatus-sets described may be modified to satisfy an almost endless number of traffic, operating, or electrical conditions. If it is desired to have lamp signals show over the line jacks at the through office to apprise the through operator that the lines involved are busy by reason of a through call handled remotely, a very simple modification in the apparatus-set at the through office will accomplish it. Further, a lamp signal might be provided at the terminal offices to apprise the operators as to the busy or

idle condition of the remote lines, obviating listening-in to determine it.

Under usual practise, through switching introduces relatively expensive operating methods, due to the fact that more operators and more line circuits are required than to handle the traffic over direct trunk lines, and direct way-lines; thus meaning lower earning efficiency to the operating company and retarded service to its patrons, the latter doubtless having a potent though intangible effect in discouraging business as well. In the first case mentioned, employing usual methods, the Portland operator desiring Tacoma would first be obliged to signal Centralia or Chehalis in the usual way and await the operator's convenience in responding; then tell this operator her wants, and again wait until she ascertained the state of the desired line, and reported back, if busy, thus consuming the time of two operators, and what is of far more moment—the time of the line. An operator establishing her own through connections by remote control avoids such delays—in fact gains all the advantages of direct trunk efficiency between points where the volume of traffic does not warrant the expense of the proper number of trunk lines to carry the maximum or "peak" demand without delaying traffic unduly, or where the advantage of direct trunk or direct way service is desired but not warranted by the traffic offered. The delays experienced in establishing through connections manually at intermediate offices are augmented by the delay in getting the established connection taken down at the termination of the service, or annoyances such as an inadvertent disconnection at the through office. In the remote control method, the withdrawing of the plug by the calling operator instantly disconnects the lines, and not otherwise.

Operators maintain that there is far less nerve strain and fatigue attaching to the remote control method of establishing through switches than with the manual method where the enforced delays under stress are very trying.

In order to facilitate "rapid fire" service between Portland and Seattle, a distance of 185 miles (297.7 km.), an unusual traffic and circuit arrangement was devised. But one trunk circuit was available, a No. 8 B. & S. copper loop having no intermediate offices obtaining service over it, and since many calls to Seattle were special calls or through calls to points beyond, it was necessary that the Portland operator should be able to signal the Seattle toll operator at will in the usual way

without disturbing the Seattle *B* operator. Following the regular line jack on the Portland switchboard is an auxiliary jack that may be called the *B* board jack, which is used when the Portland operator desires to order up a number directly via the Seattle *B* board. The Portland operator upon plugging into this jack is then able to speak directly into the head telephone of the Seattle *B* operator over the regular toll line without further preliminaries, and remains so connected until the *B* operator plugs into the called subscriber's line. Over the *B* board jack at Portland are placed two lamps which indicate by glowing that the Portland operator is not restricted by the Seattle toll operator, and further that she is in connection with the *B* operator's head telephone, and thus can proceed to order up the desired subscriber's line. The extinguishing of the

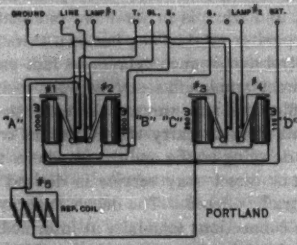


FIG. 4—TRUNKING CIRCUIT FROM TOLL LINE TO "B" BOARD (SEE FIGS. 5 AND 10)

second lamp indicates that the *B* operator has inserted the line or trunk plug into the local line jack. A lamp is placed over the jack of the line on the Seattle toll board, which by glowing indicates to the operator that the line is in use to the *B* board and is cut off at the toll board, the busy lamp being also lighted over the answering jack and its associated multiples.

The principle of operation (see Figs. 4 and 5) is that the Portland operator by plugging into the *B* trunk jack causes battery current to be projected out on the line which operates a relay at Seattle, cutting the line into the *B* operator's head telephone set, whereupon the Portland operator proceeds to ask for the Seattle, local number, just as a Seattle *A* operator would, specifying, however, "on 16," such being the number of the *B* plug associated with the toll line, as otherwise the *B* operator would not know what *B* plug to use.

This cutting into the operator's set is accomplished through the agency of relay *A*, Fig. 4, which is operated from the shell wire of the *B* board jack. The current flows through two relays in series, relays *C* and *D*. Relay *C* is adjusted to operate through a resistance of 4000 ohms, while relay *D* will not operate through a resistance of over 2000 ohms, which gives a margin of adjustment that is used to give supervision in the following manner: If the switching apparatus is on the line, that is, the Seattle toll operator has no plug in the line jack, relays *C* and *D* pick up and light the supervisory and guard lamp associated with the Portland *B* board jack, assuring the Portland operator that she has the circuit to the Seattle *B* operator's head telephone set.

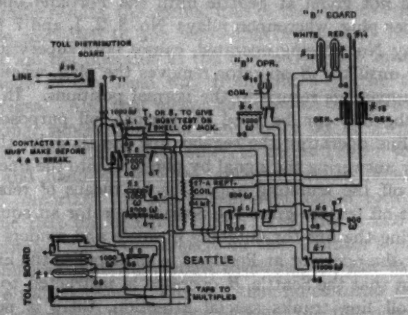


FIG. 5—LINE CIRCUIT— FOR DIRECT TRUNKING FROM TOLL LINE TO "B" POSITION (SEE FIGS. 4 AND 10)

This same current operates relay No. 3, Fig. 5, which controls relay No. 2, a cut-off relay which disconnects the line from the toll switchboard, lighting a lamp over the answering jack and also the associated multiples and thereby apprising the Seattle toll operators that Portland has the line in service via the *B* board. Relay No. 2 also operates relay No. 4 which cuts in on the *B* operator's head telephone circuit. When the *B* operator inserts the trunk plug associated with the toll line into the called subscriber's line, or into a trunk jack to a sub office, relay No. 5 operates, cutting off the *B* operator and lighting the subscriber's supervisory lamp on the *B* board. Relay No. 6 operates when the subscriber answers, extinguishing the *B* supervisory lamp, and locking relay No. 7 in an operated position until the call is released by the Port-

land operator withdrawing her switching plug. Another action of relay No. 5 is to cut the 2000-ohm resistance in series with the line relays, causing relay *D* at Portland to fall back, lighting the guard lamp No. 2 and thus giving Portland notice that the *B* plug has been inserted in the called line. When the subscriber answers and relay No. 6 is operated, this 2000-ohm resistance is short-circuited, causing relay *D* at Portland to pick up again, extinguishing the second guard lamp and apprising the Portland operator that the subscriber has answered. When the Seattle subscriber hangs up, relay No. 6 falls back, removing the short circuit from the 2000-ohm resistance, and causing relay *D* again to light its associated lamp. The clearing signal is not given at Seattle until the Portland operator removes her plug, whereupon relays No. 3, 2, 1, and 7 fall back, and relay No. 5 being operated, causes both supervisory lamps to glow until the *B* operator removes the plug, when all parts of the apparatus return to the normal positions. In this condition the line can be used for normal toll purposes, ringing on the line operating the regular line signals only, the Seattle operator answering the signal by plugging into the line jack and cutting off the trunking apparatus by means of relay No. 8. This cut-off feature gives the Seattle operator an equal chance of securing the line for outgoing business and renders it impossible for the operator at Portland to monopolize the line.

Except that the Seattle *B* operator is instructed to give the direct toll line trunks special attention, there is nothing to distinguish them in supervision from any of the local trunks, but a sounding relay associated with the lamps of the direct toll line trunks which is mounted beneath the keyshelf of the *B* board to aid in attracting the operator's attention to insure the most prompt disconnections.

Similar circuits were used between Tacoma and Seattle, provision being made also for Seattle to call Tacoma subscribers in the automatic exchange by means of an automatic calling device, which is described later in this paper. Calling with an automatic calling device as above has been tested successfully from Seattle to Portland, and there was no electrical reason for not employing it.

If, in calling Seattle numbers directly via the *B* board, the desired party was found to be out, the Portland operator would say, "have him call Long Distance 16." Upon the called party requesting this number of the Long Distance recording operator at Seattle, she understood that the call had originated at Port-

land, and after so informing him, obtaining his number, etc., would notify the operator on the Portland line who in turn notified Portland, who would complete the call via the *B* board.

Since the Northwestern Long Distance Telephone Company connected with the local automatic exchange of the Home Telephone and Telegraph Company of Portland, and local automatic exchange of the Puget Sound Home Telephone Company at Tacoma, before the latter was absorbed by the Sunset Telephone and Telegraph Company, this offered an opportunity to improve the service to those cities by permitting distant connecting exchanges on the system of the long distance company to call subscribers at Portland and Tacoma by automatic means. It was decided at the outset that to insure satisfactory operating and traffic results, the normal uses of the lines so equipped must not be restricted in any way—that is, it must be possible to signal the toll operator at the city having the automatic local exchange in the usual way from offices on the toll line, and vice versa. Also that means be provided on the toll board for checking, supervising, and listening-in on all switches called directly from the distant office, to insure proper timing of service and handling of lines, and proper discipline, the latter being important for the reason that called local subscribers assume that the operator is also local, and would censure the toll company for any breach on the operator's part, it being remembered that the distant operators are not in the employ of the toll company. Further, that no call into the automatic exchange should be possible without the toll operator of that city being immediately apprised (by means of lamp signals above the line jack) of the attempt to call, and of the response of the called local subscriber.

At the distant office two spring jacks (see Fig. 6) are provided; one for normal switching, having a signal associated therewith; the other an auxiliary jack, being used for automatic calling only. The operator first ascertains by listening-in on the regular or normal jack if the line is idle (if a way line), and then withdraws the plug and inserts it into the auxiliary jack and proceeds to "dial" the number without further preliminaries. On the completion of the dialing, two impulses are made by calling the digit "one" twice in quick succession, which rings two short bells at the called subscriber's telephone in the automatic exchange. It has been found that this method of ringing is more convenient than to ring with the regular cord-ringing-key. However, by

the introduction of an additional relay (as *E*, Fig. 1) in the apparatus set at the calling office, such cord-key ringing may be effected. In such case the distant office would ring the local subscriber in the automatic exchange in the same manner as in ringing on a direct line. The automatic exchanges referred to are what is known as the "three-wire" Strowger system, thus necessitating the use of a ground in connection with the two line wires to effect a call. In the first experiments looking towards the use of the automatic feature on the toll lines, the three-wire principle was adhered to, and gave satisfaction on those lines serving the two terminal stations only as trunk lines, but where three or more stations were served it was seen that to keep the two wires from any loop connections would involve too many complications in station equipment. Another thing that rendered the three-wire circuit on the toll line end practically out of

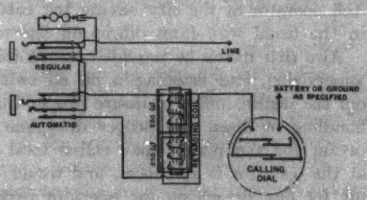


FIG. 6—CALLING OFFICE CIRCUIT, AUTOMATIC (SEE FIGS. 7 AND 10)

the question was that any kind of ringing current used for signaling between stations would vibrate the relays of the apparatus-set and cause a great deal of trouble in the automatic exchange. Due to the operating conditions of the three-wire automatic system, this would be certain to cause a great many cut-offs and extraneous noises on other lines in the local automatic exchange. The so-called "two-wire" system of calling was therefore adopted, with the necessary modifications to translate from the two-wire system on the toll line to the three-wire system on the local automatic exchange. The only difficulty met was due to the fact that in this system the connector or last switch of the series involved in making a call in the local automatic exchange drops back if the line called happens to be busy; a "vertical" impulse following, which would ring on the called line if it had been selected, serves to step the connector "off normal" and automatically gives the busy tone to the calling

party. If, however, the "vertical" impulse were followed by a "rotary" impulse, the connector would again step up and another vertical or series of vertical impulses followed by a rotary impulse would select one of the one hundred lines served by this connector, and ring some subscriber—almost certainly the wrong one. To guard against this, two different types of repeater apparatus-sets, or translators, were developed; one depending upon a small step-by-step mechanism (see Fig. 7) similar to that used in the automatic system in meter switches, and the other (see Fig. 9) depending upon a polarized relay being actuated by the proper polarity from the calling station, to eliminate the rotary impulses after the subscriber's number has been selected.

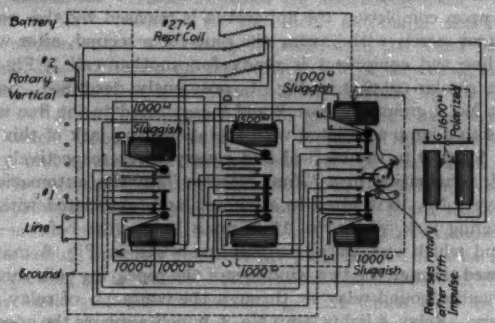


FIG. 7—TOLL LINE AUTOMATIC APPARATUS SET—REVERSES ROTARY ON FIFTH IMPULSE (SEE FIGS. 6 AND 10)

The first method is the one used in the circuit shown in Figs. 6 and 7. In Fig. 6, the two line wires are connected to a double-wound retardation coil, from the center of which the circuit can be traced through the contacts of the calling device (normally closed) to grounded battery, or if desired, to ground direct. To trace a call on these circuits, take for instance a station having the calling device grounded, and of course having battery current on the repeater (Fig. 7); normally none of the calling station apparatus is connected to the line, and it is only when the calling operator plugs into the automatic jack that it is so connected. If the toll line is free, the desired local number is obtained by rotating the calling device successively according to the digits (and letter prefix corresponding

to a digit) of the subscriber's number. If the digit 5 is called, for instance, the ground will be interrupted five times in quick succession by the calling device, after which a comparatively long pause follows while the operator is preparing to "dial" the next digit. It is this prolonged pause which is utilized to give the rotary necessarily following each digit in the three-wire system.

After the number has been selected, ringing, as before stated, is accomplished by calling two digits 1 on the calling device, giving a distinctive double ring peculiar to "Long Distance," the toll operators at the cities mentioned using a similar code in ringing subscribers. If the subscriber's line is busy the busy tone apprises the calling operator of the fact. If the called party answers, the call is handled in the usual way, and upon completion the apparatus is released by the calling operator merely withdrawing the plug for a second, after which the line and equipment is ready for another call. Fig. 7 is a set similar to that in Fig. 1, previously described, having point No. 1 grounded, Nos. 2 and 3 connected to the line wires, No. 4 to a lamp associated with the answering jack of this line, Nos. 8 and 9 to the vertical and rotary wires, respectively, of a trunk terminating in a "first selector" in the automatic exchange. No. 10 is wired to a second lamp associated with the answering jack, while No. 11 is main battery as before. The ground which was traced to the line wires in Fig. 6 may be followed through the two windings of the repeating coil, through the double-wound relay *A*, through the contacts of relay *G* to battery. Relay *A* lights lamp No. 1, which apprises the operator that a call is about to be made, also operates relay *F*, which cuts in the trunk to the automatic exchange and throws a ground on the fourth spring of relay *A*. When the calling operator manipulates her calling device, the line circuit is broken a number of times corresponding to the digit or letter called. Relay *A* falls back with each impulse and "repeats" each impulse to the vertical wire of the trunk, and also causes relay *B* to pick up, which in its turn operates relay *E*. Both *B* and *E* are sluggish relays, having a short-circuited winding or a heavy copper cylinder on one end of the core, and therefore do not fall back in the short interval between impulses, but do fall back in the longer interval between the various series of impulses corresponding to the several digits; first *B* falling back, then after a short interval, *E*. Tracing the circuit, with *E* picked up and

B in the normal position, there is a ground on the rotary side of the trunk, which serves to give the necessary rotary impulse at the end of each series of vertical impulses corresponding to the digits called. Each time relay *E* picks up, it steps up the small ratchet wheel shown in Fig. 7, the steps being held by a pawl controlled by relay *F*. Each number of the automatic exchange is composed of five digits, as *A*1000, *B*1900, *C*3211, etc., and this wheel is adjusted to complete the contact of the spring actuated by it at the completion of the fifth rotary impulse. This operates relay *C*, which reverses the automatic trunk, and disconnects the vertical impulses coming from relay *A*. When the calling device is again operated, this time to ring the subscriber, the same sequence of relay actions takes place as before, but as the vertical impulses are disconnected, the "automatic trunk" leading to the local automatic exchange is not affected until the rotary impulse, and, the trunk being reversed, this is thrown on the vertical side of the trunk, ringing the subscriber, or if the line is busy, stepping up the connector switch to "off normal," and giving the characteristic busy tone. Upon the subscriber removing the receiver, battery and ground are thrown back on the trunk from the connector switch, operating relay *D*, which lights lamp No. 2, and apprises the checking operator on the toll board that the conversation is about to begin. When the call is completed and the calling operator removes her plug, relay *A* falls back, *B* and *E* picking up as before. After about one-half second, relay *F* falls back and disconnects the ground which operates *B*, consequently, *B* falls back, followed by *E*, giving a rotary impulse as before. With *F* in a normal position, however, the automatic trunk is short-circuited, and this causes the rotary impulse to give the "short and ground" necessary to release a call in the three-wire Strowger system.

The reason the trunk is reversed instead of the rotary being merely disconnected after the fifth rotary is that a false ring would be given on release, before relay *F* fell back and released the call, thus calling the subscriber back to the telephone on a false call. Also, in case the calling operator discovered that a wrong number had been called, it would be impossible to release without giving a like false ring, all of which would not add to the prestige of the automatic system.

As stated before, grounded ringing power, or ringing power subject to grounds, must be guarded against when the switch is not in use, and this is accomplished by means of relay *G*, a

polarized relay bridged across the line. When ringing impulses come in over the line, this relay vibrates, and keeps relay *A* from securing enough current to operate.

It will be noticed that lamp No. 1 flickers with each impulse from relay *A*, and these interruptions could be utilized to operate an indicator over the answering jack, or tape register if it was considered advisable for the sake of convenience in checking calls.

In the automatic apparatus set previously described (Figs. 6 and 7), the step-by-step mechanism is utilized to eliminate the rotary impulse after the fifth digit is called, but in the repeater set about to be described (Figs. 8 and 9) a reversal of the polarity or direction of the current is depended upon to accomplish the same result. The latter method has the advantage of a more positive ringing

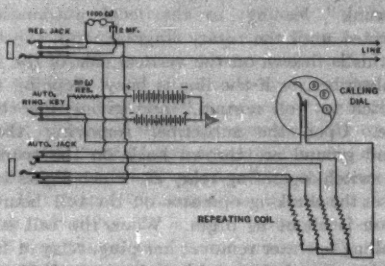


FIG. 8—AUTOMATIC CALLING CIRCUIT — CALLING STATION APPARATUS FOR POLARIZED RINGING (SEE FIGS. 9 AND 10)

control, but has the disadvantage of requiring battery current at the calling station: minus polarity for calling, and plus polarity for ringing the subscriber. While the first set described required a step-by-step mechanism, the latter requires additional relays, which, although not complicating the action of the set, still take up considerable extra space. Where the calling station has no battery supply, the former is the only choice; where battery is available, the choice is about even between the two systems, with a slight preference for the second type on account of its more positive action. The operations of calling are identical and will not be gone into in detail, but to ring the subscriber, the calling operator, using the latter circuit, depresses a self-restoring key associated with the calling device, which reverses the polarity of the battery, as can be seen

by tracing Fig. 8. This ringing of the called party in the distant automatic exchange could be accomplished by introducing a relay similar to relay *E*, Fig. 1, at the calling office, and using the usual cord ringing key.

The functions of relays *A*, *B*, *C*, *D*, *E*, and *F*, Fig. 9, in calling are practically identical with the functions of the similar relays in Fig. 7, and can be followed by reference to the preceding explanation of that circuit. The only difference is that the controlling relay *F* is operated by the polarized relay *G* (Fig. 9) which

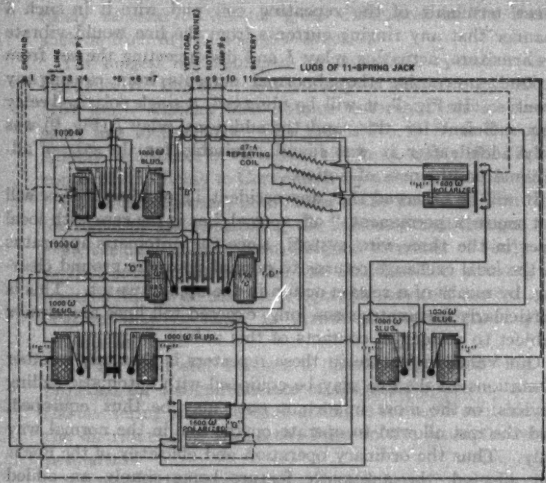


FIG. 9—AUTOMATIC TOLL LINE REPEATER APPARATUS-SET—POLARIZED RINGING CONTROL (SEE FIGS. 8 AND 10)

operates in the minus direction when actuated by the calling current. When the current is reversed by the ringing key at the calling station, relay *G* operates in the plus direction, operating relays *E* and *C*, the latter locking itself during the remainder of the call. Relay *A*, not being sensitive to directional currents, remains actuated and consequently relay *B* does not pick up. In this position, with relay *E* actuated and relay *B* normal, the rotary side of the trunk would be grounded but for the fact that relay *C* has reversed the trunk, throwing this ground on

the vertical wire instead, ringing the subscriber. The impulse wire from relay *A* is disconnected for the prevention of false rings, and local supervision by means of relay *D* and lamp No. 2, and the release at the termination of the call, are all accomplished in the same manner as shown in Fig. 7, and need not be detailed again.

In guarding against grounded ringing, it was found that on account of the extreme sensitiveness of relay *G* (Fig. 9) to such disturbances it was necessary to bridge polarized relay *H* across the inner terminals of the repeating coil and wire it in such a manner that any ringing currents from the line would vibrate its armature, actuating relay *I* and disconnecting the set from ground, preventing the abnormal currents from causing any trouble. In Fig. 7, it will be observed, a single polarized relay was sufficient for this, and the additional relay *I* (Fig. 9) was only added after it was found advisable for the sake of additional positiveness of action.

It will be observed that any accidental ground on the line will not cause a permanent "off normal," as is the case with local lines in the three-wire system, since the automatic apparatus in the local exchange returns to normal upon the ground clearing, by means of a release action in the apparatus-set. This is particularly fortunate, since long, exposed toll lines are always subject to accidental contacts of this nature.

One valuable feature in these repeaters is that any number of stations on the line may be equipped with automatic calling devices, or the more important ones may be thus equipped, and the rest allowed to operate on the line in the normal way only. Thus the ordinary operation and efficiency of the line is not affected, the automatic feature being simply an added convenience and time saver to the stations employing it.

The toll operator endeavors to check closely and time all switches called directly by automatic means by the distant operator, but in the event of heavy traffic on other lines under her care, can ignore the automatic lines and still not lower the standard of service to patrons, as no calls are retarded and the distant operator at the calling office is led to assume that her operating is being constantly supervised.

A vital condition manifesting itself in long-distance automatic operation, which does not occur in local automatic operation, is that to insure quiet long-distance lines it is necessary to introduce a repeating coil in the circuit between the long-distance

line and the local automatic equipment, that is, in the repeater apparatus-set. Also, to insure that impulses from the long lines shall be of the character to properly actuate the switch apparatus in the local automatic exchange, some method of adapting such impulses coming from the long lines to the adjustment used for the short local lines must be provided. This is done in the repeater relays contained in the apparatus-set. It is found in practise that permanent adjustments can be made so that changes are rarely necessary, even for great differences in line leakage—such as from dry to heavy weather.

The longest line equipped for automatic operation is from Corvallis to Portland, via Albany, a distance of 96 miles (154 km.). Albany also obtains automatic service over the same line to Portland. The line is No. 8 B. & S. copper to Albany, a distance of 84 miles (135 km.), and is No. 12 B. & S. copper from Albany to Corvallis, a distance of 12 miles (19 km.).

In the circuits used, both limbs of the line have been reserved for signaling and controlling the various circuit changes. However, the circuits have been designed to admit of ready change so that only one limb of the line would suffice, allowing the remaining limb to be used for telegraphic service if desired. Modifications may be made to permit the operation of phantom circuits as well.

At Portland and Tacoma a distributing board (Fig. 10) is provided for the convenience of the chief operator, permitting the answering jacks to be re-arranged for night switching or for the distribution of traffic, the lines on the multiples remaining permanent.

Supplementing the automatic and remote control methods in connection with toll lines, conveniences have been provided to facilitate the general operating as far as possible, so that the least manual effort is required in handling traffic. Such saving not only conserves the operator's time, and speeds up switching and service, but it greatly conserves the time of toll lines—the operating company's only stock in trade. At Portland and at Tacoma, the company's largest offices, call wires are provided from all operator's positions to all operator's positions. Listening keys cut off all listening keys on the cord sets ahead, so it is impossible to cut two conversations together by accidentally getting two listening keys thrown, and thus demands less attention and care on the part of operators. At the right of the cord listening keys is the supervisory key with a position call wire

lamp associated therewith, the relay controlling the lamp being mounted on the under side of the keyshelf, so that the closing of it will make enough noise to quickly attract the attention of the operator to the signal. Should the called operator be listening to a conversation at the time, she throws the supervisory key cam to the front position, which places her in connection with her call wire, cutting off the cord listening keys, and when through she returns it to the center position, when she is again supervising the cord conversation—the cord listening keys not having been disturbed. The rear position of the super-

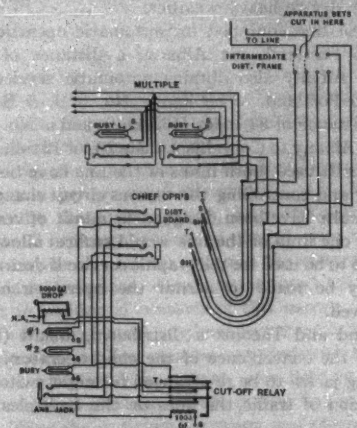


FIG. 10—OFFICE LINE CIRCUIT AT PORTLAND AND TACOMA

visory key allows unobstructed listening and talking. The center or supervisory position of the key short-circuits the secondary of the operator's telephone induction coil and cuts in a 3000-ohm non-inductive resistance. Non-inductive resistance is used in lieu of inductive resistance, since the speech may be further attenuated without rendering it unintelligible. It is not necessary to restore a listening key on a conversation should an operator desire to converse with another local toll operator—she simply depresses the corresponding order button, the cord listening keys being cut off by a relay before she gets the order wire connection; this operation being effective regard-

less of the position of the supervisory key. All supervisory circuits are so designed that no noise is discernible to conversers to whom an operator may be listening, from any manipulation of the supervisory key or order buttons. Operators can listen on front or rear cords independently, and that without first restoring the regular cord listening key of the set; that is, the cords can be cut in both directions with the normal listening key thrown to the listening position.

Reliability of action has been a first consideration in devising the equipment described. Although a circuit in which a number of functions are combined in one relay may look simpler in the circuit diagram and may even have a lesser first cost, by providing several relays with simpler and more positive action the reliability of the apparatus may often be increased and maintenance reduced.

In dealing with local exchange equipment the increased first cost due to elaborate equipment would be a fatal condition where the revenue per line is comparatively small, but where long and heavy copper circuits on expensive construction, and the time of operators, are concerned, the revenue running to several dollars per hour, the first cost of an apparatus-set as described constructed on apparently extravagant lines, is a comparatively insignificant percentage of the total investment, and therefore a relatively inappreciable capital charge. Aside from this is the consideration of not only greater service efficiency, but greater traffic efficiency as well; for observations have indicated that the increased traffic possibilities over a given line will show a gain up to 100 per cent, or even more. The use of the automatic devices may thus in instances obviate the first cost of additional outside construction, that would otherwise be called for in handling the traffic offered, together with its increased operating, interest, and attendant maintenance and depreciation charges.

There has always been a great prejudice and conservatism against the use of so-called "complicated equipment" in connection with long-distance telephone lines; perhaps because a service can be maintained without resorting to this. In long-distance telegraph and multiplex telegraph practise, we are accustomed to complicated and sensitive circuits that require conscientious watchfulness by expert attendants. There does not appear to be any well-founded reason whatsoever why equipment, requiring similar attention and equally as complicated, should not be as permissible in long-distance telephone practise

with its costly copper loop circuits, if the introduction of such complexities will facilitate service or traffic over the lines on which it is introduced, or if it will lessen the number of lines or the number of operators necessary to handle a given traffic, or both.

DISCUSSION ON "TEST OF AN ARTIFICIAL AERIAL TELEPHONE LINE AT A FREQUENCY OF 750 CYCLES PER SECOND", (KENNELLY AND LIEBERKNECHT) AND "AUTOMATIC METHODS IN LONG DISTANCE TELEPHONE OPERATION" (FRIENDLY AND BURNS), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

F. K. Vreeland: In view of what Mr. Colpitts has just said about the values of Tables III, IV and V being computed, not from the actual constants of the line given in Tables I and II, but from empirical constants derived by experiments with the line as a whole, and worked back from Table VIII I, would ask whether he can give us any information as to the agreement of these empirical constants with the actual measured constants of the line?

E. H. Colpitts: The authors give the line constants in the paper. I did not call particular attention to these tables because in the discussion of his results, Dr. Kennelly has not used the electrical constants of the artificial line at 760 periods per sec., in other words, Tables I and II are merely descriptive of the apparatus that he used.

Answering specifically Dr. Vreeland's question, I would say if you assume the "accepted mean values" of Dr. Kennelly, in Table VIII, that is, a surge impedance of $465\sqrt{11}°$ ohms, and a mean section angle of $(0.235 + j1.272)$ are correct, the line must have the following electrical constants at 760 periods per sec.

Effective resistance	119 ohms;
Effective inductance	0.0926 henrys;
Effective capacitance	0.670 mf.
Effective leakance	164 micromhos.

D. C. Jackson: While this desirable and interesting paper relates to a test of an artificial aerial telephone line using currents having a frequency of 760 cycles per second, it is, nevertheless, a paper of just as great interest and significance to the man who is working in power transmission in large bulk as to the man who is working in power transmission in very small bulk; that is, what we call heavy power transmission, on the one hand, and telephone transmission on the other. Of course, when we are working on power transmission in large bulk we are endeavoring to transmit a fundamental frequency, and to eliminate the harmonics. In the case of the telephone, on the other hand, the necessity is to transmit all the harmonics preserved in substantially equal degree over a large range of frequencies.

The significance of this paper, then, is great to both power transmission men and telephone men. One of the important papers that have come before the Institute in relatively recent years is the description of an artificial line which Dr. Kennelly published, I think, a year or two ago in the Institute PROCEEDINGS.

As I understand it, the present paper embodies the results of tests on that same transmission line, and it contains another demonstration that the formulas including the hyperbolic trigonometrical functions are highly accurate for the computation of transmission lines. That has been very well proved previously by actual telephone circuits.

As far as heavy transmission service is concerned, the frequencies are so low and the lines so relatively short that practise has not yet gone far enough to meet a quarter wave length or half wave length in actual practise, but we are surely coming to it, and it is essential that these formulas shall be studied by transmission engineers.

F. K. Vreeland: It is exceedingly interesting to me to note the close agreement between Dr. Kennelly's experimental results and the computed values, though it would be still more interesting if the computed magnitudes were computed from the beginning instead of being worked back from tests on the completed line. As everybody knows who has had occasion to work with questions of line propagation, the artificial line is a very valuable experimental adjunct, but I think, perhaps, we have all felt some doubt as to how closely the predicted results of the artificial line agree with those we get in real practise. Dr. Kennelly's tables and diagrams of computed and observed magnitudes show the degree of divergence of the "lumpy" artificial line from an equivalent uniform line, but they do not show to what extent the performance of an artificial line may be predicted from predetermined line constants. Mr. Colpitts has, however, thrown some light on this feature. I notice from the figures Mr. Colpitts has given us that there is a close agreement between the empirical constants of the line which are computed back from Dr. Kennelly's experimental results and the actual values given in Table II, except in one very important respect, namely, the apparent resistance. Mr. Colpitts gave the apparent resistance per section computed back from Table VIII as 119 ohms, whereas Dr. Kennelly gives the measured value at 760 cycles, as 33 ohms. Dr. Kennelly points out a large discrepancy between this 33 ohms at 760 cycles and the measured apparent resistance of 125 ohms at 60 cycles, which is closer to the empirical value, 119 ohms, obtained by calculating back, than it is to the measured value of 33 ohms at 760 cycles. This discrepancy is surprisingly large. Can Mr. Colpitts tell how Dr. Kennelly's measurements were derived? Is the capacity the true Maxwellian capacity, that is represented by a 90-degree leading current component, and is the inductance represented by a similar lagging component and the resistance by a pure energy component, or do those constants represent some of the multitudinous methods of measuring capacity, inductance and apparent resistance which do not give the true or Maxwellian values?

E. H. Colpitts: Unfortunately, I can not authoritatively answer Dr. Vreeland's question, because I have not discussed

the point with Dr. Kennelly. I would say, however, that the computations which we have made in order to determine what values of line constants would give the values of surge impedance and propagation constant which Dr. Kennelly found for the line, determined the effective constants at the frequency in question. In the case of the effective resistance, for instance, the value found may correspond to losses in the copper conductor alone or it would correspond to such losses plus losses in an iron core if an iron cored coil had been used. In the same way the capacity and conductance correspond to an ideal condenser, having the value of capacity which I quoted and shunted by an ideal resistance giving a conductance equivalent to the figure quoted.

George A. Campbell (by letter): The paper refers to the fundamental steady state constants of a line as its "surge impedance" and its "hyperbolic angle." Our practise is to call these constants the "iterative impedance" and the "propagation constant" and these terms seem to me preferable because the first is more exact and the other is more fundamental. It is a matter of some importance that the best terminology should be standardized, as these constants occur in almost all discussions of lines, whether uniform, loaded or artificial.

The constant referred to as the "surge impedance" applies to a steady state condition of the line and has no necessary connection with the behavior of the line towards a sudden rush of current. In general, the ratio of the electromotive force to the current is not a constant for an impulse or any other unsteady state, so that the conception of an impedance which has proved so useful in connection with steady state phenomena does not apply to transient phenomena. Heaviside's distortionless circuit is a striking exception, for with that the current which starts out on the line is always an exact copy of the applied electromotive force. If a distortionless circuit were loaded (with the first load not at the sending end) it would have a true surge impedance, which would be the surge impedance of the distorionless circuit taken alone, but its so-called "surge impedance" as that term is used in the paper would be something quite different. As this use of "surge impedance" is a misnomer, it is desirable to adopt a more exact term even if it is not quite as short or familiar.

The term "iterative impedance" is advocated for this constant because the distinguishing feature of the impedance is that it repeats itself if the line is closed through this impedance at the far end. The synonyms such as repeating, periodic, cyclic, were not considered desirable because these terms are in wide use in connection with telephone theory. In mathematics the term is already employed in this same way, the dictionary definitions being:

iterative function: "a function which is the result of successive operations with the same operator." (Century).

"a function resulting from successive operations with the same operator." (Murray).

As applied to a line the "operator" is the transformation due to a section of the line; if the line is uniform the section may be chosen of any length; if the line is of periodic recurrent structure, such as a loaded line or an ordinary artificial line, the minimum section is a periodic interval. The definition which we have adopted is:

Iterative impedance: "the iterative impedance of a line of periodic recurrent structure at a specified point, for propagation in the specified direction, is equal to the limit approached as the line is made infinite in length, by the driving-point impedance of the line beginning at the specified point extending in the specified direction, and terminating in any physically possible impedance."

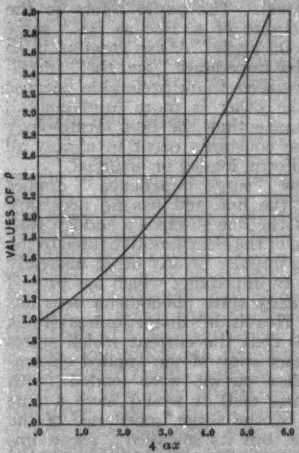


FIG. 1—AMPLITUDE CURVES FOR $\varepsilon^{x(a+i)} = \rho \text{ cis } \theta$

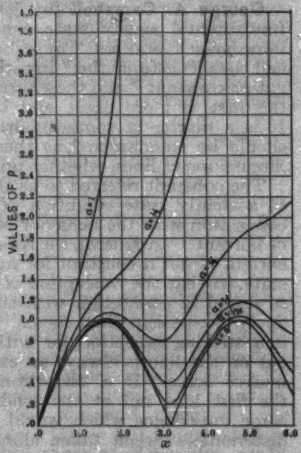


FIG. 2—AMPLITUDE CURVES FOR $\sinh x\,(a+i) = \rho \text{ cis } \theta$

This definition covers uniform lines, loaded lines and artificial lines, which may or may not be symmetrical in the two directions, and it has been made to exclude the theoretical iterative impedance having a negative resistance component by the restriction to any physically possible impedance at the far end of the line.

(Mathematically there are always two iterative impedances for each direction of transmission, one of which has a negative resistance component; the impedances for either direction are equal to the impedances for the other direction with sign reversed.)

"Propagation constant" seems to me to be preferable to "hyperbolic angle" because our basic conception of steady state cisoidal transmission over any periodical recurrent line is that it is compounded of a direct and a reflected wave, each of which falls off exponentially from one periodic interval to the next; we never picture the wave as being divided physically into a hyperbolic sine wave and a hyperbolic cosine wave. In the wave which falls off exponentially, the amplitude decreases in geometrical progression from section to section, while the phase lag increases in arithmetical progression. This is so simple that it is very easily grasped. On the other hand, the

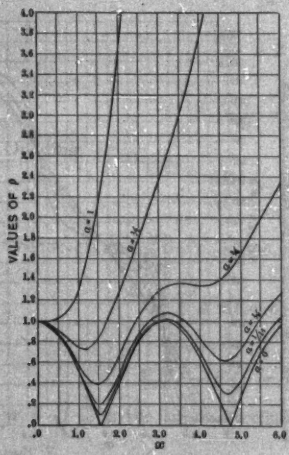


FIG. 3—AMPLITUDE CURVES FOR $\cosh x\,(a+i) = \rho \operatorname{cis} \theta$

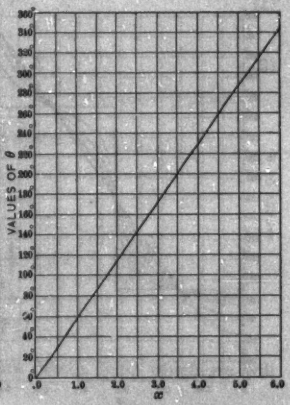


FIG. 4—PHASE ANGLE CURVES FOR $e^{x\,(a+i)} = \rho \operatorname{cis} \theta$

amplitude and phase relations in a hyperbolic sine or cosine wave are so complicated as to be grasped only with difficulty. The usefulness of hyperbolic functions of complex quantities in transmission theory is mainly confined to analytical work, and it is a matter of comparative indifference whether hyperbolic functions or circular functions of complex quantities are employed, since any expression in one form may be read in the other form without rewriting, and upon clearing the formula of imaginary quantities, hyperbolic functions and circular functions occur in equal numbers.

As hyperbolic functions are analytical means rather than

expressions corresponding to any fundamental physical phenomena, it does not seem advisable to introduce them into the fundamental terminology, while it does seem advisable to retain for the complex quantity which shows how the fundamental exponential wave varies in amplitude and phase the term "propagation constant."

Curves of amplitude and phase angle are shown by the accompanying drawings for cables ($a=1$) and ideal open wire lines ($a=0$) and also for intermediate values of the attenuation constant per wave length. For the exponential function two simple curves suffice for all cases by a mere change in the scales

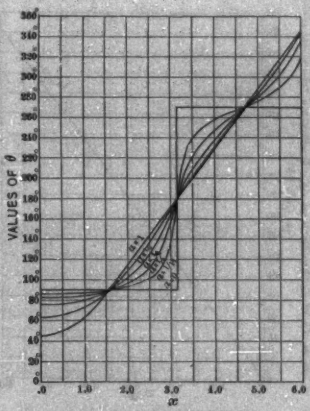


FIG. 5—PHASE ANGLE CURVES FOR $\sinh x\ (a+i)=\rho \text{ cis } \theta$

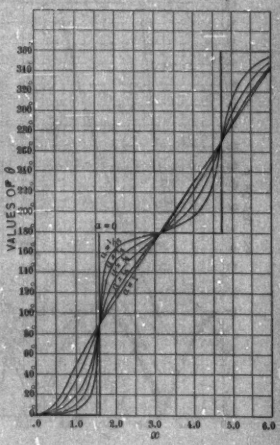


FIG. 6—PHASE ANGLE CURVES FOR $\cosh x\ (a+i)=\rho \text{ cis } \theta$

employed. To picture the hyperbolic function in the same way requires four families of curves which are comparatively complex, the individual curves becoming more and more wavy with decreasing attenuation per wave length.

R. S. Brown: In connection with the curves of current and voltage variation shown in Dr. Kennelly's very interesting paper the author would like to describe a method he has devised for plotting such curves by graphical integration. The method applies equally well to current and voltage on transmission lines, and inasmuch as all the integration is done graphically it is unnecessary to deal with exponential functions. It is

not proposed as a method for solving all transmission line problems, as here length of line is usually a constant and the conditions at some definite point are sought. Such problems are solved more directly by the use of tables of hyperbolic functions, for long lines, and approximations for short lines. This method will prove useful, however, for the solution of lines at high frequency, such as telephone lines, which are not covered by the ordinary tables, and in all cases where it is desired to investigate conditions at progressive points along the line, as in the calculation of corona loss on power lines by the quadratic law.

The well-known differential equations for voltage and current on a line with uniformly distributed constants are:

$$\frac{dE}{dl} = Z\,I \tag{1}$$

$$\frac{dI}{dl} = Y\,E \tag{2}$$

Dividing,

$$\frac{dE}{dI} = \frac{Z}{Y}\,\frac{I}{E}$$

The integration of this equation gives

$$Y\int_{E_0}^{E} E\;dE = Z\int_{I_0}^{I} I\,d\,I$$

$$Y\,(E^2 - E_0^2) = Z\,(I^2 - I_0^2)\,.$$

or, if $\sqrt{\frac{Z}{Y}}$ is the surge impedance of the line, which we will call S,

$$E^2 - S^2\,I^2 = E_0^2 - S^2\,I_0^2$$

Let

$$F = \sqrt{E_0^2 - S^2\,I^2} \tag{3}$$

The quantity F, then, is the same for every point on the line if the line be free from taps.

Solving for I,

$$I = \frac{1}{S}\sqrt{E^2 - F^2}$$

But

$$\frac{Z}{S} = \sqrt{Z\,Y} = \theta$$

where θ is the hyperbolic angle subtended by the line in vector radians per mile.

$$\frac{dE}{dl} = \theta \sqrt{E^2 - F^2} \tag{4}$$

Hence

$$\frac{dE}{\theta\, dl} = \sqrt{(E + F)(E - F)}$$

Since l is a real number it is seen that the angle of $\frac{dE}{\theta}$ is one-half the angle of $(E + F)$ plus one-half the angle of $(E - F)$. This angle may be found by bisecting the angle at the vertex

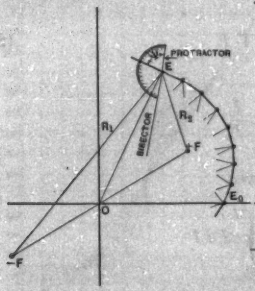


FIG. 1

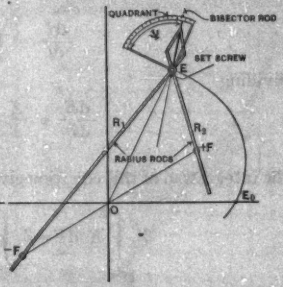


FIG. 2—PLAN VIEW OF INTEGRAPH.

of the triangle formed with $\pm F$ as base and $(E - F)$ and $(E + F)$ as sides. The angle of dE will then be the angle of θ in advance of the bisector, see Fig. 1. This angle of θ, which we will call φ, depends merely upon the construction constants of the line.

If

$$Z = r + j\,x$$

$$Y = g + j\,b$$

$$\tan \delta = \frac{x}{r} \qquad \tan \epsilon = \frac{b}{g}$$

$$\varphi = \tfrac{1}{2}(\delta + \epsilon)$$

For lines with zero leakage, $g = o$.

$$\varphi = 45^\circ + \tfrac{1}{2}\delta$$

Here, then, is a means of plotting the voltage curve. Being the solution of a second order differential equation, it will involve two constants of integration and these are F and E_0. These being laid off on the diagram, the voltage curve may be plotted by drawing a series of connected chords, starting from the point E_0. Each of these chords will be laid off with a protractor φ degrees in advance of the bisector drawn to the point. By a similar construction the current curve may be drawn, except that in this case the constants of integration will be G and I_0, where

$$G = \sqrt{I_0^2 - \frac{E_0^2}{S^2}} \tag{5}$$

From the foregoing it is seen that the current and voltage curves may be defined geometrically as—The locus of a point

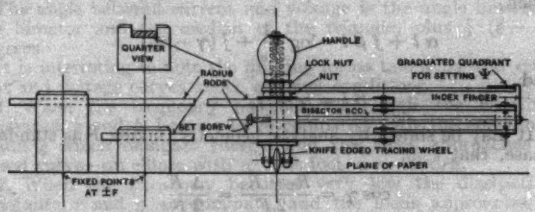


FIG. 3—ELEVATION OF INTEGRAPH

which moves so as to make a constant angle with the bisector of an angle drawn from the point to two fixed points.

Obviously the accuracy of this method will depend upon the shortness of the chords, or, for a given length of chord, upon the radius of curvature. To increase the accuracy the author has constructed an integraph as shown in Figs. 2 and 3. It consists of two steel rods sliding through fixed supports at $\pm F$. The intersection of the rods lies over the point E. Beneath the intersection is a knife-edge tracing wheel which is free to move only in the direction of its plane, being constrained from motion in the direction of its axis by the friction of the knife edge on the paper. By means of a graduated segment and a set screw the plane of the tracing wheel may be set at the angle φ with the bisector of the angle, and it will maintain this angle as it is moved over the paper, tracing out the locus of E. The paths of the wheel may be preserved by placing a piece of carbon paper over the region to be traced. Aside from electrical curves, the instrument may be used to plot any ellipse, or hyperbola, since all these curves obey the above law.

This method would be incomplete without being able to assign to any point on the curve, the lengths of line corresponding. This length is found as follows: The integration of equation (4) gives

$$\theta\, l = \log \frac{E + \sqrt{E^2 - F^2}}{E_0 + \sqrt{E_0^2 - F^2}}$$

Let

$$\frac{E + \sqrt{E^2 - F^2}}{E_0 + \sqrt{E_0^2 - F^2}} = \frac{A\, \sigma^{j\gamma}}{A_0\, \sigma^{j\gamma_0}}$$

and

$$\theta = (\alpha + j\,\beta)\, l$$

where

$$\alpha = \text{Attenuation constant}$$

$$\beta = \text{Wave length constant.}$$

Then,

$$\alpha\, l + j\,\beta\, l = \log \frac{A}{A_0} + j\,(\gamma - \gamma_0)$$

and

$$\beta\, l = \gamma - \gamma_0$$

It may be shown by analytic geometry, taking F as standard phase, that

$$\cos\gamma = \frac{R_1 - R_2}{2\,F} = \frac{\Delta\, R}{2\,F}$$

R_1, R_2, and F being the scalar values.
Hence

$$\beta\, l = \cos^{-1} \frac{\Delta R}{2\,F} - \cos^{-1} \frac{\Delta\, R_0}{2\,F}$$

Let the length corresponding to the point E_0 be l_0, then

$$l_0 = \frac{1}{\beta} \cos^{-1} \frac{\Delta\, R_0}{2\,F}$$

and

$$l = \frac{1}{\beta} \left(\cos^{-1} \frac{\Delta R}{2\,F} - l_0 \right)$$

In lines having zero leakage, the wave length constant

$$\beta = \frac{\omega}{\sqrt{2}\, V} \sqrt{1 + \csc\delta}$$

where V is the velocity of wave propagation, approximately that of light. In this case,

$$l = \frac{\sqrt{2}\, V \cos^{-1} \frac{\Delta R}{2F}}{\omega \sqrt{1 + csc\, \delta}} - l_0$$

Instead of plotting the current curve, the current corresponding to any point on the voltage curve may be found from the relation

$$S I = \sqrt{E^2 - F^2}$$

The magnitude of the current is

$$I = \frac{\sqrt{R_1 R_2}}{S}$$

R_1, R_2, and S being the scalar values.

The angle between current and voltage is the angle between the bisector and the median of the triangle, plus $\frac{1}{2}(\delta - \epsilon)$ degrees.

It is interesting to note the limiting forms taken by the current and voltage curves under extreme conditions.

1. When the frequency becomes very high the reactive constants, x and b, become large compared with the constants r and g which dissipate energy, and the locus approaches a closed curve—an ellipse with $\pm F$ as foci, $\varphi = 90$ deg.

2. When the frequency becomes very low the dissipative constants, r and g, predominate, and the locus approaches a hyperbola with $\pm F$ as foci, $\varphi = 0$.

3. When $I_0 = 0$ (no load) the locus of E becomes the graph of $\cosh \theta l$.

4. When $E_0 = 0$ (short circuit) the locus of E becomes the graph of $\sinh \theta l$.

5. When the line approaches infinite length the distorting factor, F, due to the reflected wave, disappears and the locus becomes a logarithmic spiral. This factor also disappears when the impedance of the load is equal to the surge impedance of the line, in which case the generator wave is entirely absorbed by the load and no reflection ensues.

6. When the conditions mentioned in 5 obtain and the reactive constants predominate, the locus approaches a circle.

The distortion noticed in Dr. Kennelly's curves for the first wave length or so is due to the reflected wave. As a greater distance from the open end is attained, the reflected wave becomes damped out and all the curves approach logarithmic spirals.

J. B. Taylor: While abstracting his paper, Mr. Friendly remarked that while a technical engineer might be disposed to object to some of the automatic devices described, the commercial engineer would be satisfied that the use of the additional devices and complications had justified itself.

While I have no reason to assume that the particular arrangements described in this paper may be in any way detrimental to the service, I wish to remark that, in general, there is some risk in going so far with automatic devices that the actual telephone service (*i.e.*, the transmission of speech from one subscriber to another, neither of whom is interested in the modes of operation of the devices by which the communication is established) is impaired.

To illustrate this point, mention need only be made of the undesirable and frequently painful, if not dangerous, noises to which we are subjected when using telephones connected to certain common battery systems. The original magneto systems, while undesirable in many respects, were less noisy.

H. M. Friendly: In reply to Mr. Taylor's remarks, if you will look over the circuits carefully you will find that nothing has been introduced in the circuits of the equipment which will attenuate speech appreciably, such as is the case in some types of telegraph equipments applied to telephone lines.

In regard to the noises referred to, we have made a particular effort to avoid extraneous noises of every kind; and in the latter part of the paper our views will be found on that phase. I agree with Mr. Taylor very thoroughly in that extraneous noises on a telephone line, the humming and clicking, are very detrimental to service. The conversers will invariably pause after a clicking sound and then shout at each other to ascertain if they have been cut off, and it is sometimes a large fraction of a minute before they get under way again after the disturbance has ceased. In all the apparatus designed we made it a first consideration to eliminate disturbances.

Oberlin Smith: It seems to me that any advance toward automatic service should be welcomed and should be developed and discussed. We all know there are tremendous difficulties in telephone exchange work of any kind, sometimes even in pleasing subscribers.

Taking an optimistic view, I do not think there is any question but what in the sometime golden future, I will not say when, all telephony will be automatic, and we will talk all over the world by merely arranging our own instrument, with its buttons or levers, or what not, for the connection desired. We should welcome all improvements in this line as steps towards the ultimate automatic telephony which may extend its arms all over a continent, if not indeed to the ends of the world.

H. M. Friendly: In regard to the reliability of the apparatus, we have not found the apparatus to give serious maintenance trouble at all. The switch sets look complicated on paper, though in a period of some months' test no adjustments were made in any manner to the connecting switch of the through switch switching set, though changes were made in circuit details on several occasions in the development of the apparatus.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright 1913. By A. I. E. E.

ELECTROLYTIC CORROSION OF IRON IN SOILS

BY BURTON MCCOLLUM AND K. H. LOGAN

The term electrolytic corrosion is most frequently used to indicate corrosion caused by the discharge of an electric current which enters the metal from external sources. During recent years, however, the theory has been widely accepted that all corrosion in water solutions is essentially electrolytic in its nature, and in consequence there have come into use a variety of terms such as "galvanic action," "stray current electrolysis," "self-corrosion," etc., to distinguish between the cases of corrosion originating from different causes. Thus corrosion of buried iron may be due to galvanic action caused by physical or chemical differences between adjacent points on the surface of the metal, to the presence of foreign substances in the soil such as coke, cinders, iron oxides, etc., which set up local galvanic action, or it may be due to the discharge of electric currents that have entered the structure at some remote point. In the present paper the terms "electrolysis" and "electrolytic corrosion" are used to designate corrosion caused by the discharge of electric current which has entered the metal from some outside source, while all other forms of corrosion in which the electric currents originate within the corroding system itself from whatever cause, are referred to as "self-corrosion." It should be pointed out at the outset, however, that these two general classes of corrosion are by no means independent of each other, since the presence of either kind of corrosion generally affects in marked degree the nature and extent of the other, under a given set of conditions. This mutual influence is such as to be of considerable practical importance, and in particular it often greatly increases the difficulty of obtaining

trustworthy experimental data in regard to electrolytic corrosion proper.

The data herein presented represent a portion of the work done by the Bureau of Standards in connection with a more general investigation of the subject of electrolysis and electrolysis mitigation, which has been in progress for some time past. The present paper is designed to deal only with the fundamental laws governing electrolytic corrosion under practical conditions, and relates to self-corrosion only in so far as it is necessary to distinguish between the two classes. The subject of the prevention of electrolytic damage is referred to only incidentally when occasion requires in order to interpret the significance of results obtained. This matter of electrolysis has been given much attention, but is far too comprehensive a subject to be dealt with in a brief paper such as can be presented here. It will be treated at some length, however, in a report which will be issued shortly by the Bureau of Standards, dealing exclusively with the subject of electrolysis mitigation.

In studying the phenomena of electrolytic corrosion in soils under practical conditions, many variables are encountered which tend in greater or less degree to affect the results. Among these may be mentioned the current density at the surface of the metal, the moisture content of the soil, and the presence of oxygen either in the gaseous state or dissolved in soil waters. The latter not only affects the rate of corrosion but also affects the character of the end products of the reactions and thus to some extent has a bearing on the question of diagnosing the cause of particular cases of corrosion. The temperature of the soil is also important, particularly because of its effect on the current flow. In the case of iron, the formation of oxides as a result of the initial corrosion may complicate matters because of their possible effect in stimulating galvanic action. Other factors, such as the mechanical and chemical properties of the soil, the depth of burial of the metal, the limitation of current flow due to polarization, the formation of high-resistance films on the surface of the metal, and the pitting of the surface due to a variety of causes, may likewise act to increase or decrease the rate at which damage may progress, and therefore require special investigation. Finally, since it is not practicable to carry on all experiments in the field under practical conditions, it is necessary to study the possible differences in results that may in some cases occur between experiments performed in

the laboratory and in the field. It is these factors that are dealt with in the following pages, and while the investigations have in most cases not yet been completed, we believe that the data thus far obtained will be of sufficient interest to justify a report of progress at this time.

While the corrosion of iron by electric currents may be influenced by a variety of causes, nevertheless the data to be presented later show that under most practical conditions the extent of the corrosion is largely a function of the quantity of electricity that is discharged from a given surface. This is a quantity that can be readily measured under laboratory conditions and we have therefore determined, in all cases, the corrosion as a function of the ampere-hour discharge from the anode. The results are expressed in terms of the "corrosion efficiency." If the corrosion of the anode is the sole action involved at the anode, then, according to Faraday's law, 96,540 coulombs are required to corrode one gram-equivalent of the metal, and the corrosion efficiency is said to be 100 per cent. In most cases, however, the actual corrosion noted is either greater or less than this amount, and the percentage which the actual corrosion, in any case, is of the theoretical amount, is called the "efficiency of corrosion" under those conditions. The experimental data presented in the first part of this paper show how the efficiency of corrosion is affected by the varying physical conditions encountered in practise. The corrosion efficiencies are in all cases calculated on the assumption that the iron is divalent. The experiments presented show that in most cases, at least, this is true, since, as a rule, the corrosion efficiencies observed have been near or above one hundred per cent. This is therefore the logical basis on which to figure the efficiency of corrosion. In those cases where the corrosion efficiency was very low it may have been due in part to the iron taking the ferric state, and such tendency, when it exists, may therefore be regarded as one of a number of possible causes of low efficiency of corrosion. The various factors enumerated above which affect the efficiency of corrosion of iron in soils, are discussed in detail in a later part of this paper.

Arrangement of Apparatus

The methods of conducting the experiments recorded below were in general the same, and may, therefore, be described once for all.

The local earths used in the laboratory tests were from virgin soil near the laboratory, sifted to remove stones and to insure uniformity. This earth was mixed with the desired amount of distilled water and placed in tin cans which served as cathodes. The bottoms of the cans were separated from the earth by a thick layer of paraffin or other insulating material so that the discharge from the anode placed in the center of the can would be substantially uniform and only toward the sides of the can. The outsides of the cans were insulated from each other by several layers of heavy paraffined paper. In a number of experiments, however, the test specimens were buried in virgin soil out of doors in order to compare directly the corrosion found under these conditions with the corrosion which resulted when the tests were made in the laboratory.

Cleaning of Anodes

In cleaning the anodes and determining their losses, a number of precautions are necessary. It has been shown that many solutions render iron at least temporarily passive. Such solutions are, of course, not desirable for cleaning iron previous to a test. The iron used was filed and sandpapered to remove dirt and scale, cut into suitable lengths, stamped on one end for identification with steel numbers, and weighed. Rubber-covered leads were then soldered to the unnumbered ends of the anodes and both ends covered with paraffin or pitch. To make these stick to the iron it is necessary that it should be rather hot when they are applied. The specimens were then thoroughly washed with gasoline to remove any grease due to handling and finally dried with a towel. At the close of the experiment the specimens were washed and brushed to remove all loose dirt and then made cathode in a two per cent solution of sulphuric acid with a high current density. To prevent plating a non-corrodable anode should be used. This method of cleaning was developed after various mechanical and chemical methods had been tried with inconsistent results, and has proved very satisfactory. The specimens came from the solution perfectly clean within ten to thirty minutes and careful tests have shown that clean iron subjected to the treatment suffers no loss.* The method seems very much preferable to any mechanical method we have tried, because, when the rust sticks very tightly or the iron is rough, it is impossible to remove the

*This does not apply to cast iron.

corrosion products without scraping off some of the iron with them. In a few instances where it was not convenient to clean the iron electrolytically, as in the case of hollow anodes too small to permit the interior to be protected by inserting an anode, a solution of ammonium citrate has been used. This latter method is satisfactory except in the case of deep pits, especially if a warm solution is used.

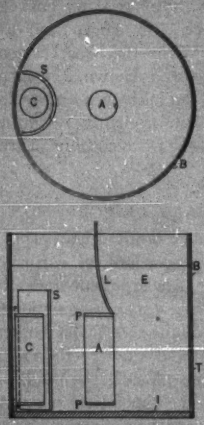


FIG. 1—ARRANGEMENT OF ANODE AND CHECK SPECIMEN

A—Anode 1¼ in. diam.; B—paraffined paper, 2 layers; C—check specimen 1¼ in. by ¼in. diam.; E—earth; I—paraffine ¼ in.; L—lead No. 18 rubber covered; P—pitch layer; S—glass shield one inch diam.; T—tin can 3 in. diam., 3¼ in. high.

The paraffin protecting the ends of the specimens was removed by gasoline and the pitch by toluol. The solder attaching the leads was melted and carefully wiped off. We have also tried dissolving the solder by mercury but the process is slow unless heat is used, and the result no better than the easier method.

CHECK SPECIMENS

Correction for the loss by the anodes due to self-corrosion was made by placing a check specimen inside each can and screening it from the anode by a shield of glass or paraffined paper. Fig. 1 shows the arrangement of the anode and check specimen. The loss of the check specimen has been deducted from the loss of the anode and the difference used as the loss due to electrolysis. It will be shown later that the loss of a check specimen in a can with an anode is considerably greater than that of a similar check specimen in a separate vessel of the same earth and it seems therefore that part of the loss in the former case is due to some effect of the current and should be against it. The corrosion efficiencies found are therefore charged lower than if check specimens in separate cans were used. However, there are several advantages in keeping the check specimen in the can with the anode, and the increased loss on this account is usually small, compared with the total loss of the anode.

Determination of Ampere-Hours

To obtain the corrosion efficiency it is, of course, necessary not only to determine accurately the loss of the anode, but equally essential to know the quantity of electricity discharged by it. To obtain this, the specimens were so arranged that the currents could be read at frequent intervals, compensation being provided where necessary for the resistance of the milliammeter. Curves were plotted showing the relation between current and time, and the area between the curve and the axes determined with a planimeter. While the exact current values between times of observation are unknown, the areas represent a value of the ampere-hours sufficiently accurate for practical purposes, and the large number of circuits operating at one time made the use of more accurate recording instruments out of the question.

I. FACTORS AFFECTING EFFICIENCY OF CORROSION

1. *Effect of Current Density.* A number of investigators have reported experiments showing that the amount of corrosion which results from a given ampere-hour discharge varies greatly from the theoretical amount. Among these may be mentioned the work of Hayden[1] and of W. W. Haldane Gee [2] who worked with high current densities, and observed that there was a marked tendency for the iron to become passive, the resulting corrosion being considerably less than the theoretical amount. In general, this tendency toward passivity was much more marked when the current density was made very high. These experiments were carried out with test specimens immersed in liquid baths, however, so that the conditions were very different from those which prevail in ordinary street soils. Ganz[3] has reported the results of experiments carried out in certain soils, which showed that the actual corrosion observed was much greater than the theoretical amount, in some cases the loss in weight being as much as several times the loss calculated from Faraday's law. In these experiments very low current densities were used and the earth contained considerable quantities of salt and this may have affected the result. The authors have carried out several series of experiments in which the aim

1. *Journal of the Franklin Institute*, Vol. CLXXII, p. 295.
2. *Journal of the Municipal School of Technology*, Manchester, Vol. 2, 1910.
3. Trans. A. I. E. E., 1912, Vol. XXXI, p. 1167.

has been to maintain conditions as nearly as possible approximating those which will be encountered in practise, both as regards soil conditions, and current densities. The soil used was a virgin soil taken from a sparsely settled portion of the residential district of Washington. An analysis was made of a typical sample of the soil for those ingredients which are most likely to affect corrosion, the results being shown at the top of Table I along with the data on efficiency of corrosion. In determining the current densities to be used, values were chosen of such magnitude as could give rise to considerable injury within a period varying from a few months to fifteen or twenty years. For example, the highest value used was about 5 milliamperes per square centimeter, which under uniform distribution and at 100 per cent efficiency of corrosion would cause the corrosion to progress inward at the rate of about 5.7 centimeters per year, which corresponds to a rate rarely exceeded under practical conditions. The minimum current density used was 0.05 milliamperes per square centimeter, which corresponds to a normal rate of corrosion of about one centimeter in 17 years. These extreme ranges represent, therefore, the limits between which the corrosion is of much practical importance.

Several series of experiments were made, the data presented in Tables I and IA being typical of the series. The corrosion efficiencies under Table I are for a soil containing considerably less moisture than those under Table IA, which were obtained in a soil practically saturated with water. In the former the test specimens were all imbedded in samples of earth placed in tin cans as described above, while in the second series half of the tests were run with specimens buried to a depth of about 2½ ft. (76 cm.) in the ground out of doors.

The data in Table I are plotted in Fig. 2, and those of Table IA are plotted in Figs. 3 and 4, the curve of Fig. 4 being a continuation of that of Fig. 3, but on a smaller scale. While the points do not lie on a smooth curve, because of a number of disturbing factors to be discussed later, the trend of the curves is nevertheless unmistakable. They show corrosion efficiencies varying greatly with the current density, the ranges being from about 20 to 140 per cent for the range of current density varying from about 5 to 0.05 milliamperes per square centimeter, the lower corrosion efficiencies being obtained at the higher current densities. All of the data in Tables I and IA are plotted as a single curve in Fig. 5, which, in spite of

TABLE I

RELATION BETWEEN CURRENT DENSITY AND EFFICIENCY OF CORROSION

PARTIAL ANALYSIS OF SOIL USED IN TESTS

Cl_2	NO_3	CO_3	SO_4
0.002%	0.002%	0.003%	0.004%

No.	Current Density milliamps. per sq. cm.	Efficiency of corrosion
1	2.0	57.6
2	1.8	37.4
3	1.7	69.2
4	1.6	43.2
5	1.5	84.3
6	1.3	75.8
7	1.2	72.8
8	1.1	83.8
9	1.0	89.2
10	0.8	75.0
11	0.7	88.3
12	0.6	79.1
13	0.5	75.2
14	0.4	102.1
15	0.3	142.2
16	0.2	96.2
17	0.1	148.4
18	0.05	142.9

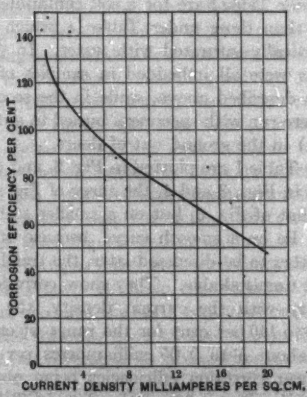


FIG. 2—CORROSION EFFICIENCY—CURRENT DENSITY

the irregularities in the individual points, shows clearly the decided falling off in efficiency of corrosion with increase in current density. It is interesting to note here that the points in Fig. 5 marked with an *X* were taken out of doors in native earth while those marked with dots and circles were two separate

TABLE Ia

CURRENT DENSITY-CORROSION EFFICIENCY

AREA OF ANODES, 70.9 SQ. CM. TIME OF RUN, 115 HOURS

No.	Current density milli-amps. per sq. cm.	Corrosion efficiency
19	0.034	124.1
20	0.064	115.0
21	0.088	141.5
22	0.129	123.6
23	0.150	104.6
24	0.163	118.3
25	0.206	125.8
26	0.222	117.1
27	0.258	101.8
28	0.279	113.4

CURRENT DENSITY-CORROSION EFFICIENCY

72-HOUR RUN IN SATURATED SOIL IN LABORATORY. 4–27–13 TO 4–30–13. EXPOSED ANODE AREA, 11.78 SQ. CM.

No.	Current density Milliamps. per sq. cm.	Corrosion efficiency
29	0.48	102.5
30	1.01	98.1
31	1.26	78.3
32	1.84	102.2
33	2.28	63.6
34	2.50	78.1
35	3.45	52.9
36	4.27	43.6
37	4.20	27.4
38	4.72	20.4

series taken indoors, using small samples of earth in cans. The agreement between the different groups is fully as good as that between different points of the same group, which indicates that the results obtained on small samples in the laboratory are substantially the same as those obtained on specimens

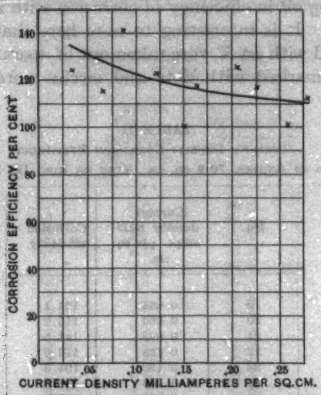


FIG. 3—CORROSION EFFICIENCY—CURRENT DENSITY

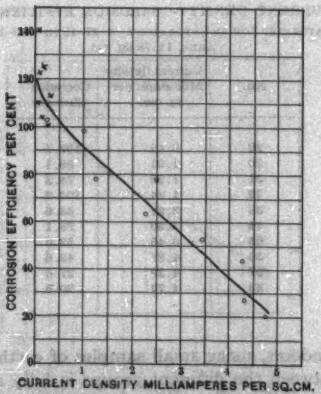


FIG. 4—CORROSION EFFICIENCY—CURRENT DENSITY

buried in the earth out of doors. This gradual change in corrosion efficiency with current density does not appear in accord with the results of Hayden, Haldane Gee, and others, whose work with liquid electrolytes seemed to indicate an abrupt change in efficiency of corrosion from 100 per cent to zero at a critical current density.

It will be noted that these results do not show as high efficiencies of corrosion as those reported by Prof. Ganz[4], who found values ranging over 500 per cent. It should be noted, however, that the results obtained by Prof. Ganz were for the most part obtained on much lower current densities than were used in the present experiments. It is seen also from Fig. 5 that as the lower current densities are approached the curve tends rather strongly upward, indicating that if the current density

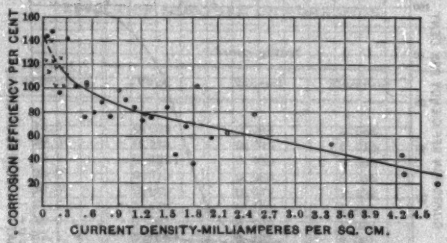


FIG. 5—CORROSION—CURRENT DENSITY

had been reduced to the low value used by Ganz, the corrosion efficiencies might have reached the high values found by him. As pointed out above, however, lower current densities than those used in the present series, although of great theoretical interest, are of little consequence from the practical standpoint.

2. *Effect of Moisture on the Rate of Corrosion.* The following experiment was tried to determine whether the amount of moisture in the soil affected the corrosion efficiency of iron buried in it:

A quantity of red clay soil was air-dried and then distilled water was added, a can of earth taken out; more water added, etc., till twelve cans of earth had been obtained.

The ends of the specimens and the bottoms and outsides of the cans were insulated as in previous tests, and small dishes

4. TRANS. A. I. E. E., 1912, Vol. XXXI., p. 1167.

of water placed inside the cans to retard evaporation. The six cans were connected in series, the sides of the cans serving as cathodes, and a current of two milliamperes giving about one milliampere per square centimeter, was maintained by daily adjustments for 86 days. At the end of this time the resistance had increased so much that it was difficult to maintain the current and the specimens were therefore removed, cleaned and weighed. The efficiency of corrosion was then computed, corrections being made for self-corrosion.

While the current was flowing, samples of the earth, taken when the specimens were placed in the cans, were dried for about a week in an oven at a temperature of 105 deg. cent. and the percentage of moisture computed from the loss of weight. The

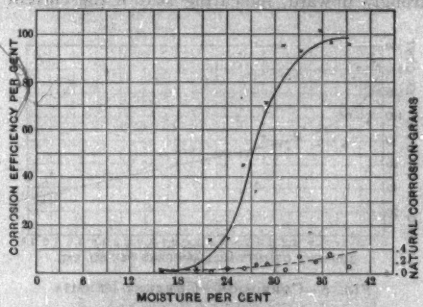


FIG. 6—CORROSION EFFICIENCY MOISTURE
Natural corrosion moisture

per cent of moisture is expressed in terms of the earth before drying.

The result of this test is given in Table II, and plotted in Fig. 6.

Looking at the curves of self and electrolytic corrosion, it will be seen that where a point on one curve is too high, the corresponding point on the other curve is too low. Since the electrolytic curve was obtained after natural losses had been deducted it is evident that part of the irregularities is due to incorrect values of the natural loss. However, the natural loss is so small that in most cases it could not account for the entire variation in the electrolytic curve. Since all wrought iron contains more or less slag it is probable that the presence

of minute slag particles explains, in part at least, the pitting and variations of results from expected values.

The results of these tests show that the corrosion efficiency varies greatly with the moisture content of the soil, being so small as to be practically negligible when the soil is fairly dry, but approaching values of the order of 100 per cent when the soil becomes saturated. In these tests there was very little corrosion when the moisture content was below 20 per cent. It should not be assumed, however, that the numerical values given here will hold for all soils, since there is considerable uncertainty as to the conditions which actually prevail.

In the first place, the percentage of moisture required to produce a wet condition of the soil varies greatly with different

TABLE II

EFFECT OF MOISTURE ON CORROSION

No.	Per cent moisture	Loss—grams			Per cent efficiency
		Total	Natural	Electrical	corrosion
1	15.9	0.090	0.044	0.046	1.1
2	20.0	0.110	0.040	0.070	1.6
3	22.5	0.623	0.039	0.584	13.7
4	23.8	0.715	0.080	0.635	14.9
5	26.0	2.002	0.073	1.929	45.3
6	27.6	1.579	0.145	1.434	33.7
7	28.9	3.192	0.160	3.032	71.2
8	31.1	4.182	0.121	4.061	95.4
9	33.3	4.217	0.265	3.952	92.8
10	35.7	4.545	0.207	4.338	101.9
11	37.0	4.463	0.335	4.132	97.0
12	39.4	4.218	0.125	4.093	96.2

soils, so that the percentage of moisture cannot be taken as a measure of the condition of dryness. In the red clay soil used in these tests the soil appeared to be barely moist at 15 or 20 per cent moisture; whereas in many cases we have since encountered numerous soils in which 10 per cent of moisture caused it to appear quite wet. There may also be variations due to differences in soil composition which affect the efficiency of corrosion. Further, while the average current density in these experiments was maintained practically constant, it is not improbable that the actual current density varied considerably. When the soil was practically saturated with water the current density would probably be nearly uniform, but as the moisture content is reduced and some of the pores in the soil became voids,

there would be a tendency for the current to discharge locally at the points of contact between earth and iron, and it appears possible that this might give rise to great variation in the actual current density of the discharge. It has already been seen that at high current densities the efficiencies of corrosion tend to become smaller, so that the variations in efficiency of corrosion here observed as due to changes in moisture content, may after all be due in large part to changes in current density. However this may be, the important fact is that the amount of corrosion per ampere-hour is likely to be quite low in the case of fairly, dry soils whereas, as the percentage of moisture approaches that corresponding to saturation, the corrosion efficiency approaches 100 per cent for the particular value of current density used in this series, namely, one milliampere per square centimeter.

3. *Effects of Temperature.* In order to study the effects of temperature on the efficiency of corrosion of iron in soil, three series of experiments were carried out. In the first of these, the temperature of the cans containing the earth samples was maintained practically constant at between zero and one deg. cent. by means of an ice bath; the second was run at between 24 and 27 deg. cent., which corresponds to about average summer temperature in soils, and the third group was maintained at between 35 and 40 deg. cent. by means of an automatically regulated oven. Four specimens were used in each group, and the current density was maintained practically constant at about 0.84 milliamperes per square centimeter.

The tests were all run in the same kind of earth, which was kept practically saturated with moisture. The results of these tests are given in Table III. An examination of the values of efficiency of corrosion will show that they are practically independent of the temperature. It appears, therefore, that it is safe to assume that throughout the range of temperatures that is likely to be encountered under practical conditions, temperature variations have no marked effect on the corrosion efficiency of iron in soils. This does not mean, however, that temperature is not an important factor in electrolysis under practical conditions, for the reverse is true; but this grows out of the effect of temperature on the resistance of the soil rather than on the efficiency of corrosion. It is shown in a later part of this paper that the resistance of soils varies with temperature in a very remarkable manner, even within the ranges of temperature that

are likely to occur in soils under ordinary conditions, and that the effect of this change in resistance on the current flow is such as to make the actual amount of electrolysis which may be expected, vary greatly with temperature. This matter is discussed later under the head of earth resistance.

4. *Effect of Depth of Burial on Efficiency of Corrosion.* Inasmuch as the efficiency of corrosion is found to vary greatly under different conditions, it was deemed advisable to investigate whether the depth to which a pipe is buried below the surface would have any effect on the efficiency of corrosion. Accordingly a number of specimens were prepared and buried in earth

TABLE III

EFFECT OF TEMPERATURE ON CORROSION EFFICIENCY

No.	Temperature	Corrosion efficiency
	deg. cent.	98.2
1		103.4
2	35 to 40	97.0
3		98.4
4		
	Average	99.2
		98.2
5	24 to 27	97.6
6		97.9
7		97.6
8		
	Average	97.8
9		93.8
10	0 to 1	95.7
11		99.1
	Average	96.2

Average current density 0.84 milliamperes per sq. cm.

to distances varying from a few inches to about six feet. A check specimen was provided in each case to permit correction for self-corrosion, and it was so shielded as to prevent the passage of any current through it. The anodes and check specimens alternated with each other in the order given in Table IV. In correcting for self-corrosion the mean of the losses on the check specimens on both sides of each anode was used. The specimens were buried in virgin red clay soil and were run at an average current density of about 0.056 milliamperes per sq. cm. for about 1490 hours. The results of the tests are shown in Table IV and plotted in Fig. 7, which gives curves of both self-corrosion and efficiency of corrosion as a function of depth. It wil

1

be seen that the results, while somewhat irregular, indicate that there is but slight variation attributable to depth, although there seems to be a trend upward in the case of self-corrosion. The variation in efficiency of corrosion with depth is probably due to the fact that the moisture content varied with depth. The fact that no greater variation was observed is doubtless due to the fact that the tests were carried out at a time when the soil was fairly wet, both near the surface and at greater depths. The results given above on the effect of moisture content indicate that if the experiments had been made in a fairly dry time when there was considerable variation of moisture content with depth, the corrosion efficiency would probably have shown a

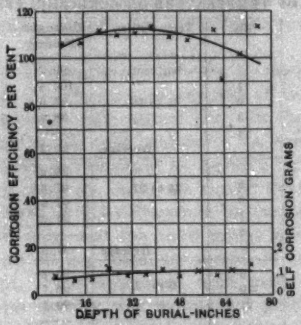


FIG. 7—CORROSION EFFICIENCY—DEPTH

corresponding variation. When conditions are such that there are considerable variations in moisture content with depth, as in a moderately dry time for instance, the preceding data indicate that the efficiency of corrosion would probably also vary greatly with depth, being in general, greater the greater the depth.

5. *Effects of Oxygen on Corrosion of Iron.* Since, according to the electrolytic theory of corrosion, the presence of oxygen is an essential factor in the production of self-corrosion of iron in the presence of water, it might be expected that the electrolytic corrosion of iron by stray currents would be affected in a marked degree by the content of dissolved oxygen in soil water. In order to investigate this point, ten anodes and a corresponding number of check specimens having an exposed area of 90 sq.

cm. each were prepared in the usual way and connected in series and run on a practically constant current density of 0.056 milliamperes per square centimeter. Five of these jars were so arranged that oxygen bubbled through the liquid continuously throughout the entire experiment, and the other five were immersed in the water without oxygen being

TABLE IV

EFFECT OF DEPTH OF BURIAL ON NATURAL AND ELECTROLYTIC CORROSION

WROUGHT IRON CYLINDERS 2 IN. (5.08 CM.) LONG AND 1¼ IN. (3.4 CM.) IN DIAMETER, POLISHED. ODD NUMBERS CARRIED CURRENT. EVEN NUMBERS ARE FOR NATURAL CORROSION

No.	Total loss	Electrical loss	Loss theoretical	Per cent efficiency	Depth
					Inches
1	9.260 g.	7.972 g.	6.990 g.	114	75
2	1.288				72
3	9.475	8.319	8.119	102	69
4	1.024				66
5	7.630	5.685	6.280	91	63
6	0.875				60
7	10.862	9.929	8.785	113	57
8	0.901				54
9	9.422	8.512	7.890	108	51
10	0.829				48
11	8.505	7.593	6.950	109	45
12	0.995				42
13	8.822	7.866	6.942	113	39
14	0.916				36
15	8.225	7.341	6.618	111	33
16	0.852				30
17	6.890	5.913	5.385	110	27
18	1.120				24
19	7.331	6.424	5.780	111	21
20	0.694				18
21	4.667	3.993	3.732	107	15
22	0.654				12
23	5.092	4.420	4.226	105	9
24	0.690				6

Area of surface 70.9 sq. cm.
Mean current density about 0.059 milliamperes per sq. cm.

passed through them. At the end of 183 hours the experiment was completed and the anodes were weighed and efficiencies of corrosion calculated. The data are given in Table V, from which it will be seen that there is considerable variation in the efficiencies of corrosion for the individual specimens. These variations are so large that the difference between the average of the five specimens in the jars through which oxygen was

passed (98.5 per cent), and the average for those specimens in the remaining jars (91 per cent), has but little significance. It is, of course, necessary to bear in mind in interpreting these results that even the water through which oxygen was not passed, contained a good deal of oxygen in solution, so that any differences in efficiency of corrosion that might be indicated would be those due to a somewhat indefinite difference in the oxygen contained in the water.

TABLE V

EFFECT OF OXYGEN ON EFFICIENCY OF CORROSION

CURRENT DENSITY 0.056 MILLIAMPERES PER SQ. CM. TIME 183 HR. AREA OF ANODES 90 SQ. CM.

A—OXYGEN ADDED

No.	Total loss	Self-corrosion	Electrical loss	Per cent efficiency of corrosion
0	1.248g.	0.182g.	1.066g.	110.7
1	1.251	0.312	0.939	97.5
2	1.296	0.330	0.966	100.5
3[1]	0.993	0.067	0.929	96.5
4	1.128	0.327	0.801	87.0
			Average	98.5

B—NO OXYGEN ADDED

5[1]	0.886	0.030	0.873	90.6
6	0.940	0.027	0.913	94.9
7	0.913	0.029	0.884	91.7
8	0.889	0.030	0.859	89.0
9	0.895	0.040	0.855	88.7
			Average	91.0

1. Buried in sand.

In order to check this result more carefully, two series of experiments were carried out in which a much larger difference in the oxygen content in the two cases was maintained. In each series four specimens were used, two being placed in tap water and the other two in a 10 per cent solution of sodium sulphate. In one series the liquids were first boiled down to half their original volume in Erlenmeyer flasks to remove oxygen, and the iron electrodes inserted during boiling. After the boiling, an atmosphere of hydrogen was introduced into

the flasks as they cooled down, so that practically no oxygen could have access to the liquid. In the other series air was caused to bubble through the liquid throughout the experiment so that an abundant supply of oxygen was always present. The results are given in Table VA. From this table it will be seen that there is no appreciable difference between the efficiencies of corrosion in the presence of oxygen and in the absence of oxygen, at least in the liquid electrolytes here used. We have reason to believe, however, that this is not the case when the anodes are buried in soils, although just why a difference should

TABLE VA

EFFECT OF OXYGEN ON EFFICIENCY OF CORROSION

WEIGHTS

No.	Solution	Original	Final	Loss	Per cent corrosion efficiency
		WITHOUT OXYGEN			
1	H_2O	51.326g.	50.624g.	0.702g.	96.2
2	H_2O	51.570	50.871	0.699	95.8
3	10% Na_2SO_4	52.361	51.651	0.710	97.3
4	10% Na_2SO_4	51.642	50.935	0.707	96.9
				Average	96.5
		WITH OXYGEN			
5	H_2O	51.852	51.154	0.698	95.7
6	H_2O	52.725	52.044	0.681	94.7
7	10% Na_2SO_4	51.467	50.759	0.708	97.0
8	10% Na_2SO_4	51.034	50.317	0.717	98.2
				Average	96.4

Theoretical loss, 0.730 g.
Area of anodes, 15.2 sq. cm.
Current density, 1.45 milliamperes per sq. cm.

exist here is not clear. That there is a difference is borne out by a number of tests we have made with anodes buried in earth in hermetically sealed cans and others buried in cans exposed to the atmosphere, conditions as to moisture content, current density, etc., remaining the same. Whenever the tests were continued for a considerable time it was found that the efficiency of corrosion in the sealed receptacle was in nearly all cases considerably lower than when the container remained open. This effect is shown in Table VI.

The average corrosion efficiency in the closed cans was 85.5 per cent while that in the open cans was 105.7 per cent.

Whether or not this difference is due to the difference in the amount of oxygen or CO_2 present or to other causes, it affords another indication of the danger of drawing conclusions from experiments made in liquid electrolytes as to what would occur in the case of electrodes buried in soils.

6. *Effect of Oxygen on the End Products of Corrosion.* One very marked effect of oxygen on corrosion, however, is its influence on the final products of electrolysis. There is a very common impression extant that the final products of corrosion of iron due to stray currents are the black oxides, whereas in the case of self-corrosion red oxides are produced. This is not in

TABLE VI

CORROSION EFFICIENCIES IN OPEN AND CLOSED CANS

No.	Efficiency of corrosion	
	Closed cans	Open cans
1	87.9	
2	77.4	
3	95.2	
4	79.9	
5	95.4	
6	77.2	
7	85.8	
8		106.5
9		105.5
10		105.3
11		105.5
Average	85.5	105.7

Average current density, 0.494 milliampere per sq. cm.
Area of anodes, 9.4 sq. cm.

accord with accepted theories of corrosive processes, and the following experiments have been carried out in order to demonstrate that in general this is not the case, although under certain circumstances the tendency may be in that direction.

Four tests were made in which ingot iron was allowed to corrode naturally in the absence of oxygen, one test being in distilled water, two in tap water, and one in 10 per cent Na_2SO_4 solution. Four tests were made in which the iron was allowed to corrode naturally in the presence of oxygen, two tests being in distilled water and two in tap water. Four tests were made in which the iron was allowed to corrode electrolytically in the absence of oxygen, the electrolyte being tap water in two of the tests and 10 per

cent Na_2SO_4 solution in the other two. Four tests were also made in which the iron was allowed to corrode electrolytically in the presence of oxygen, two tests being in tap water, and two tests in 10 per cent Na_2SO_4 solution.

The solutions were prepared practically free from oxygen by boiling down to about half their original volume in Erlenmeyer flasks. The iron test pieces were introduced during the boiling, and after the boiling was stopped the flasks were closed off from the air and a current of hydrogen free from oxygen was allowed to pass into the flasks as they cooled down, thus keeping the solutions under an atmosphere of hydrogen.

In the case of the natural corrosion tests in the absence of oxygen, the iron showed no corrosion at first, but after a day or two a few spots of greenish-black rust were noted, which gradually became larger as time went on, with the formation of a small amount of yellow ferric oxide. This was probably due to the fact that the air gradually diffused in through the rubber connections. In the case of the natural corrosion tests in the presence of oxygen, the rust was soon apparent and consisted almost entirely of the yellow ferric oxide. Thus we see that when oxygen is almost entirely excluded, the ferrous oxide predominates, and when oxygen is present, the ferric oxide predominates.

In the case of the electrolytic corrosion tests, the eight flasks were connected up in series, and a current of about 0.025 amperes allowed to pass for about 27 hours. At the end of this time the current was stopped and the anodes were taken out and weighed and the loss in weight determined. It was found that the corrosion efficiency was practically 100 per cent in all cases, calculating with iron having a valence of two. In the case of the four flasks from which air was excluded, the iron was practically all in the ferrous condition, the corrosion products having the pale green color of the hydrated ferrous oxide. Analysis of the corrosion products in one of the flasks gave 98.9 per cent ferrous iron, the slight oxidation being probably due to the unavoidable introduction of air into the flask during the removal of the electrodes for weighing. Through two of the other four flasks a current of air was allowed to bubble during the course of the electrolysis, and in those two flasks the corrosion products had the reddish yellow color of the hydrated ferric oxide, showing that the iron was largely oxidized to the ferric condition. The other two flasks were left open to the air, but air was not bubbled

through, and in these flasks the corrosion products had a darker color and when filtered off, dried, and tested with a magnet showed the presence of considerable magnetic oxide. Evidently then the corrosion had proceeded so fast that there was not enough oxygen present to oxidize the oxide completely to the ferric condition, but in the other case where air was bubbled through the solution, the solution was kept saturated with oxygen and so the oxide was converted completely to the ferric condition.

These results show that when iron corrodes electrolytically, it corrodes as the ferrous oxide and that the formation of higher oxides is due to the oxidation of the ferrous oxide by the oxygen of the air, the degree of oxidation depending on the rate of corrosion and the concentration of the oxygen. If the rate of corrosion is relatively rapid and the concentration of the oxygen is relatively low, there will be a predominance of the lower oxides, *i.e.*, the ferrous oxide and the magnetic oxide; on the other hand, if the reverse is the case, *i.e.*, if the rate of corrosion is relatively low, there will be a predominance of the ferric oxide.

The same explanation will apply to natural corrosion. In this case the rate of corrosion is very slow and so the ferric oxide predominates; and even when the oxygen is almost entirely excluded, the rate of corrosion is so slow that there is a slight formation of ferric oxide, although the ferrous oxide predominates.

From the foregoing it will apear that the character of the end products of corrosion does not depend essentially on the cause of the corrosion, but that either of the oxides may be produced, both in the case of self-corrosion, and in the case of electrolytic corrosion. It may, however, throw some light on the question in many circumstances, for the reason that the rate of natural corrosion of pipes imbedded in earth may usually be expected to be so low that practically nothing but the ferric oxides would be produced, there being enough oxygen in the soil waters to oxidize any ferrous iron that may be formed. In the case of electrolytic corrosion, however, this will not always be the result, the corrosion being so rapid, especially under bad electrolysis conditions, that the supply of oxygen in the ground waters will not be sufficient to oxidize all of the ferrous iron, and the result will be the formation of a considerable amount of magnetic oxide. This, however, will no doubt be largely affected by the depths of the pipe below the surface. The deeper the pipes,

as a rule, the less would be the available supply of oxygen, and the greater would be the tendency for the formation of the magnetic oxide. Pipes very close to the surface, even though corroding very rapidly by stray currents, might still form little if any magnetic oxide, because of the abundant supply of oxygen that would be available. Nevertheless, wherever a large preponderance of magnetic oxide exists, while it does not definitely prove that the corrosion has been due to stray currents, it may usually be regarded as a good indication that the rate of corrosion has been so great as to make it altogether probable that stray currents have been largely responsible, unless soil conditions, such as the presence of cinders, coke, chemicals, etc., are such that extremely rapid self-corrosion may be indicated.

7. *Relative Electrolysis in Different Kinds of Iron.* The question as to relative tendencies of different kinds of pipe to suffer damage due to electrolysis has often been discussed, and there appears to be a well-defined feeling in many quarters that a marked difference of this sort exists. It seems to be the general impression that cast iron pipes are much less susceptible to electrolytic damage than wrought iron or steel pipes. Experience indicates that cast iron pipe does offer less trouble from electrolysis than other kinds under most conditions. It has long been well known, of course, that certain kinds of iron are more resistant to self-corrosion than others, wrought iron, as a rule, being more durable under ground than steel, and cast iron suffering less than either. Since the experimental data presented later in this paper show that the natural corrosion is affected in a marked degree by the presence of stray currents, it might reasonably be supposed that different kinds of pipes would also suffer in widely varying degrees from stray current corrosion. In order to determine to what extent this might be the case, a considerable number of experiments have been carried out, using different kinds of iron that are employed in commercial service for underground pipes. Four kinds of iron were used, namely, ingot iron, which is the purest commercial iron known, wrought iron, machine steel and cast iron. Two series of experiments were run on cast iron, in one of which the cast iron was machined to a clean surface and in the other the iron was used just as it came from the mold, without removal of the scale. The test specimens weighing about 30 grams each were placed in a red clay soil practically saturated with water and run in series on a constant current so that the same number of ampere-hours was discharged

from each test specimen. The results are shown in Table VII. Since the current in all specimens was the same, and the size of the test specimens practically the same, giving about 0.2 milliamperes per sq. cm., the figures shown in the column under "electrical loss" are directly comparable for the different kinds of iron, and show the relative tendency of the iron to corrode electrolytically under conditions of the test.

TABLE VII

COMPARATIVE CORROSION EFFICIENCY FOR INGOT, WROUGHT AND CAST IRON AND MACHINE STEEL

No.	Total loss	Self-corrosion	Electrical loss (Check in can)
		1—Ingot Iron	
0	1.704 g.	0.015 g.	1.689 g.
3	1.678	0.033	1.645
4	1.848	0.051	1.797
5	1.669	0.031	1.638
6	1.791	0.043	1.748
7	2.243	0.046	2.197
8	1.665	0.041	1.624
9	1.583	0.074	1.509
10	1.688	0.036	1.652
11	1.713	0.060	1.653
12	1.706	0.033	1.673
13	1.676	0.042	1.634
14	2.167	0.055	2.012
15	1.661	0.028	1.633
16	1.679	0.076	1.603
17	1.674	0.046	1.628
18	1.648	0.058	1.590
19	1.647	0.057	1.590
		Ave. 0.046	Ave. 1.695
		2—Machine Steel	
20	1.658	0.052	1.606
23	1.734	0.076	1.650
24	1.827	0.062	1.765
25	1.721	0.066	1.655
26	1.672	0.064	1.608
27	1.694	0.076	1.618
28	1.684	0.113	1.571
29	1.756	0.087	1.669
30	1.644	0.031	1.613
31	1.653	0.046	1.607
32	1.792	0.066	1.726
33	1.761	0.059	1.502
34	1.686	0.033	1.653
35	1.695	0.063	1.632
36	1.808	0.066	1.742
37	1.734	0.066	1.668
38	1.818	0.109	1.709
39	1.694	0.059	1.635
		Ave. 0.066	Ave. 1.652

No.	Total loss	Self-corrosion	Electrical loss (Checks in can)
	3—Wrought Iron		
40	1.713	0.160	1.533
43	2.203	0.077	2.126
44	1.789	0.065	1.724
45	1.712	0.063	1.649
46	1.689	0.117	1.572
47	1.842	0.094	1.748
48	1.756	0.116	1.640
49	1.693	0.069	1.624
50	1.659	0.048	1.611
51	1.201	0.114	1.087
52	1.701	0.124	1.577
53	1.661	0.068	1.593
54	1.852	0.055	1.797
55	1.684	0.068	1.616
56	1.646	0.050	1.596
57	1.712	0.073	1.639
58	1.713	0.076	1.637
59	1.840	0.080	1.760
		Ave. 0.084	Ave. 1.696
	4—Cast Iron, Surfaced		
60	1.807	0.120	1.687
63	1.700	0.305	1.395
64	1.846	0.108	1.738
65	1.757	0.283	1.474
66	1.769	0.177	1.592
67	1.746	0.079	1.667
68	1.808	0.136	1.672
69	1.939	0.082	1.857
		Ave. 0.161	Ave. 1.635
	5—Cast Iron Unsurfaced		
70	1.712	0.136	1.576
71	1.435	0.255	1.180
74	1.810	0.047	1.763
75	1.709	0.060	1.649
76	1.868	0.245	1.623
77	1.710	0.135	1.575
78	1.662	0.252	1.410
79	1.712	0.060	1.652
		Ave. 0.149	Ave. 1.553

An examination of these figures shows that there is but little difference in the amount of corrosion in the different kinds of iron. This is particularly true of the wrought iron, machine steel and machined cast iron, which show respectively 1.696, 1.652, 1.635 grams loss. The ingot iron showed a somewhat higher electrolytic corrosion than any of the others, which seems to be somewhat surprising in view of the fact that it has frequently been demonstrated that the self-corrosion in the case

of ingot iron is less than others. The least corrosion of all was in the case of the unfinished cast iron, and this is probably due to the protective effect of the scale, but even here the difference is hardly great enough to be considered of practical importance. The conclusion that must be drawn from these figures is that the efficiency of electrolytic corrosion of the different kinds of iron pipes is practically the same. If we examine the columns showing the self-corrosion in different kinds of iron we find very surprising differences. These check specimens were placed in the can along with the anodes and carefully shielded from the flow of current as in all previous cases. An examination of these data shows that the ingot iron gave the least self-corrosion of all, the average for all the specimens being 0.046 grams. Machine steel came next with a total natural loss of 0.066 grams; wrought iron is third with 0.084 grams; and last, and most surprising of all, the self-corrosion of the cast iron is very much higher, being 0.161 for the machined iron and 0.149 for the unfinished iron. This shows very little difference between the finished and unfinished cast iron in the matter of self-corrosion in the presence of current flow.

The relatively high rate of self-corrosion of cast iron as compared to the other kinds of iron tested is contrary to the generally accepted idea that cast iron is more resistant to self-corrosion than wrought iron. It is not improbable that this impression in regard to the superiority of cast iron has grown out of the fact that cast iron structures are usually made relatively heavy and they also tend to corrode more uniformly than wrought iron or steel, both of which factors would tend greatly to increase the life of the former. The principal cause of the greater rate of self-corrosion of cast iron appears to be the galvanic action set up between the free carbon and the iron. The carbon is distributed so uniformly throughout the mass, however, that no appreciable pitting results, and hence the corrosion is less conspicuous and also less important than the same amount of corrosion would be if not uniformly distributed, as is usually the case with most other kinds of commercial iron. It should be pointed out here that these tests were carried out in the same kind of soil as that used in securing the data of Table I, and the partial analysis there given shows it to be low in chlorides, sulphates, carbonates and nitrates. It was likewise free from cinders, coke, etc., and hence is not to be regarded as a very corrosive soil. It is shown later in this paper that the chemical constituents in

the soil have a marked influence not only on the total corrosion, but also on the pitting, or uniformity of the corrosion, so that it should not be assumed that the relative values given here will hold for all soils.

The foregoing results show that the different kinds of iron do not in themselves differ materially as regards their tendency to corrode electrolytically. It would appear from this that the differences noted in practise, particularly in favor of cast iron, are due to various other causes, as has already been pointed out by Prof. Ganz and others, namely, higher-resistance joints, higher specific resistance of the iron, the heavier walls, and a tendency to corrode more uniformly.

8. *The Effect of Certain Chemicals on the Corrosion of Wrought Iron in Earth.* When pipes are buried in the streets, they are subject not only to the action of the moisture and various natural constituents of the soil, but also to the effects of such chemicals as may result from the traffic on the streets, or from other sources.

A large amount of work has been done by other investigators on strips of iron immersed in aqueous solutions and it has been shown that the resulting corrosion is a function of the amount as well as the character of the chemical used. In many cases the tendency towards self-corrosion first increases with the concentration and later diminishes very rapidly, possibly to zero, when the concentration is sufficiently increased.

It is well known also that certain solutions, such as alkalis, chromates, etc., tend strongly to inhibit electrolytic corrosion, at least when such solutions are practically pure. Hayden has shown that solutions of chromates, for example, tend to produce passivity in iron and thus prevent electrolytic corrosion, but that this passivity is destroyed by the addition of a few hundredths of one per cent of a chloride or a somewhat greater quantity of sulphate. It was considered advisable to carry out a series of experiments with iron imbedded in earth to which various chemicals had been added.

For these experiments a number of acids, bases and salts as indicated in Table VIII were secured and two grams of each were added to 300 g. of distilled water. The solution was added to 700 g. of air-dried red clay, which had been sifted through a 20-mesh sieve. This earth contained initially about 5 per cent of moisture, so that the resulting mixture contained about 33 per cent water, which produced a fairly wet earth. The

TABLE VIII

EFFECT OF CHEMICALS ON CORROSION RESULTS

Chemical	Can No.	Solubility g. per liter	Solution used g. per liter	Chemical value g. per liter	Critical value g. per liter	Limiting value g. per liter	Efficiency of corrosion at 0.55 ma. per sq. cm.	Natural loss mg. per sq. cm. per day	Corrosion eff. obtained by Hayden 1% sol., 22 ma. per sq. cm.
								B. S.	
CH_3COOH	2		5.715	0.0957			102.5	0.100	
$KMnO_4$	28	63.4	5.715	0.0364	0.1	0.1–1.0	90.2	0.166	
$BA(NO_3)_2$	34	92.0	5.715	0.0441			123.2	0.150	
$(NH_4)NO_3$	10	1924.0	5.715	0.0719	0–500	1155	116.3	0.265	37.8
$Na\ NO_3$	16	880.0	5.715	0.0677	0.1	632	104.2	0.152	
$K\ NO_3$	22	316.0	5.715	0.0571			89.6	0.238	25.0
$H\ NO_3$	4		5.715	0.0914			85.4	0.506	
Average							103.7	0.262	
$Ba\ Cl_2(2H_2O)$	31	357.0	4.874	0.0479	0	374	106.0	0.136	
$Ca\ Cl_2(2H_2O)$	25	427.0	2.890	0.0526			101.8	0.159	
$H\ Cl$	1		5.715	0.1579			101.6	0.270	
NH_4Cl	7	372.0	5.715	0.1076	1.0	290	101.4	0.496	102.3
$K\ Cl$	19	340.0	5.715	0.0772	50.0	299	98.6	0.222	102.2
$Na\ Cl$	13	3582.0	5.715	0.0985	0	395	97.8	0.239	
Average							101.2	0.253	
$Na_2SO_4(10H_2O)$	18	194.0	2.520	0.0360	10.0	400	89.2	0.136	
K_2SO_4	24	111.0	5.715	0.0661	0—	108	88.9	0.170	102.8
$Ba\ SO_4$	36	0.002	5.715	0.0494			87.7	0.231	
H_2SO_4	6		5.715	0.1174			87.4	0.329	
$(NH_4)_2CO_4$	12	754.0	5.715	0.0873	0.200	534	86.0	0.316	102.7
$Ca\ SO_4(2H_2O)$	30	2.0	4.520	0.0669	0		85.9	0.174	
Average							87.5	0.226	

TABLE VIII. *Continued.*

EFFECT OF CHEMICALS ON CORROSION RESULTS

Chemical	Can No.	Solubility g. per liter	Solution used g. per liter	Chemical value g. per liter	Critical value g. per liter	Limiting value g. per liter	Efficiency of corrosion at 0.55 ma. per sq. cm.	Natural loss mg. per sq. cm. per day	Corrosion eff. obtained by Hayden 1% sol., 22 ma. per sq. cm.
								B S.	
$Ba(OH)_2(8H_2O)$	32	39.0	3.104	0.0365	0	3.1	93.1	0.322	
NH_4OH	8	526.0	11.770	0.6965			88.7	0.591	
$KOH(2H_2O)$	20	1120.0	3.480	0.0348			85.6	0.611	
$NaOH(1H_2O)$	14	1090.0	3.942	0.0993	0.1	1.0	81.7	0.608	
HOH(Av.)	3& 33						73.9	0.258	
$Ca(OH)_2$	26	1.6	5.715	0.1556	0	0.67–1.35	73.5	0.195	
Average							82.7	0.431	
K_2CO_3	21	1120.0	5.715	0.0834	1.0	1–10	89.3	0.306	2.75
$Na_2CO_3(10H_2O)$	15	275.0	2.107	0.0201	1.0	10	85.4	0.394	
$(NH_4)_2CO_3$	9	1000.0	5.715	0.1225			81.7	0.561	38.2
$CaCO_3$	27	0.01	5.715	0.0719	0.0003	0.28	66.2	0.348	
Average							80.6	0.402	
$BaCrO_4$	35	0.004	5.715	0.0455			45.0	0.189	
$(NH_4)_2CrO_4$	11	405.0	5.715	0.0762			0.4	0.003	
$CaCrO_4(2H_2O)$	29	142.0	4.643	0.0600			0.3	0.136	
K_2CrO_4	23	632.0	5.715	0.0593	0	0.1 up	0.3	0.163	
$Na_2CrO_4(10H_2O)$	17	813.0	2.829	0.0354			0.3	0.062	
CrO_3	5	657.5	5.715	0.1143	0	0.01–0.05	0.2	0.122	
Average								0.116	

whole was thoroughly mixed and placed in a quart tin fruit can provided with a friction top.

The anodes were prepared as in experiments already described and vessels of water were placed in the cans as in previous experiments and the cans connected in series; first, in one group, finally, on account of increased resistance, in three. The current was adjusted daily to 0.005 ampere, which gave a current density of discharge of about 0.45 milliampere per sq. cm.

At the end of 85 days the experiment was discontinued, the cylinders cleaned as previously described and the losses computed.

In Table VIII the substances have been grouped according to the anions formed.

Since in a number of cases more salt was used than the water could dissolve, the solubility of each chemical has been indicated. This is followed by the number of grams of the anhydrous salt used, per liter of water. Then follows the chemical value of the solution, *i.e.*, the number of grams of salt per liter of water multiplied by the hydrogen value of the anion and divided by the molecular weight of the salt.

Then follow two columns of values obtained from Hein and Bauer's "On the Attack of Iron in Water and Aqueous Solutions."[5] The first is the concentration of solution giving maximum corrosion; the second the concentration producing passivity or minimum corrosion. Hein and Bauer suspended small iron plates in beakers of solutions of concentrations from zero to saturation. Their researches in this line are more extensive than any other work so far reported.

While their experiments cannot be compared with the one now recorded on account of differences in conditions, the values quoted may indicate at what part of the corrosion-concentration curve the present tests were made, from which we may form some estimate as to the manner in which the corrosion would have changed if the concentration had been varied. The efficiency of corrosion is given in the following column, and this is followed by the natural loss in milligrams per sq. cm. of surface of the iron per day.

Referring to the efficiencies of corrosion given in column 8, it will be seen that with the exception of chromium compounds the efficiencies of corrosion are comparatively high.

5. "*Mitteilungen aus dem Königlischen Material prüfungsamt.*", 1908 Berlin 26, 1.

All of the soluble chromates seem to protect the iron from electrolytic corrosion, though this protection is not quite complete. In the case of chromium trioxide the loss at the anode was slightly less than that of the check specimen. No significance should be attached to this result until after further investigation. The comparatively slight protection shown by barium chromate is no doubt due to its very slight solubility.

None of the other chemicals which Friend, Hein and Bauer or Hayden have found to render iron passive in solutions seem to have been effective. Indeed, excepting the chromates, there are but two values less than the average corrosion efficiency when distilled water was used.

The anodes in cans containing chromates were blackened and making the iron cathode in 2 per cent H_2SO_4 for half an hour did not remove the discoloration. The check specimens were not discolored in this way.

That the hydroxids did not protect the iron may have been due to the presence of materials in the soils which neutralized them. There was no doubt quite a little CO_2 in the soil, since it had been dried, crushed and sifted in the laboratory and had stood there in an open barrel for some time, and this may have been sufficient to counteract the effect of the hydroxids.

As will be seen by comparing columns 4 and 7, the concentrations used in the case of the hydroxids and carbonates were in nearly every case greater than those producing passivity when the solution alone acts on the iron. The difference in the results may be due to the effect of the earth on the solution or to the effect of the current. It seems clear, however, that the conditions which prevent self-corrosion are not in general those which will maintain passivity in the case of anodes discharging current at moderate current densities. There does not appear to be any very definite relation between the corrosion efficiency observed and the self-corrosion. The nitrates and chlorides, for instance, show respectively 103 and 101 per cent efficiencies of corrosion with corresponding value of self-corrosion of 0.262 and 0.263 mg. per sq. cm. per day. The hydroxids and carbonates show lower corrosion efficiencies, namely, 82 and 80 per cent respectively, but the natural corrosion is much higher, being 0.431 for the hydroxid and 0.402 for the carbonate. The soluble chromates show almost a complete absence of electrolytic corrosion; whereas the self-corrosion, although smaller than in the other cases, is by no means so small in proportion. It will be seen,

also, that the corrosion efficiencies observed do not agree with the values found by Hayden[6] and shown in column 10. While a part of this difference may be due to the differences in solution strength and current density, it is probably due for the most part to the fact that the tests in the present instance were carried out with anodes imbedded in earth, whereas the experiments of Hayden were carried out in water solutions.

It does not seem probable that a sufficient quantity of inhibiting chemicals can be added to the soil surrounding a buried pipe to protect it indefinitely at a reasonable cost. To render the pipe passive is one problem; to maintain it passive against fluctuating or even reversing currents, regardless of the action of the soil and the constantly changing soil waters on the soluble chemical, is quite another.

A phenomenon of importance which is not shown in the tabulated data, is the pitting of the iron. This is usually attributed to particles of impurities in the surface of the iron or to variations in the soil. In these experiments the virgin soil was dried, rolled and sifted through a 20-mesh sieve. Enough solution was added to nearly saturate the soil. All of the cylinders were cut from the same piece of Norway iron rod. It might be expected, therefore, that the pitting would be very similar in all cases. This, however, was by no means the case. The anodes from the nitrate cans were covered by a dark cheese-like layer which maintained the original form of the anode. When this was pared off the surface of the iron was nearly smooth, showing the fibrous structure of the wrought iron, but no pits. The anodes in the cans containing sulphates were corroded almost as uniformly, but the surface of the cleaned anodes was brighter and somewhat uneven, but with no marked pits. The surface of the anodes from the carbonate cans was more uneven. Pitting is noticeable in the case of the hydroxides and very marked in anodes from the cans containing chlorides.

As has been stated, the soluble chromates blackened the surfaces of the anodes but did not materially attack them otherwise. There are no marked differences in the appearance of the check specimens except that those from the chromate cans remained bright. So marked are the differences in the anodes that in most cases it is possible to classify them by their appearance, without reference to their numbers.

As underground pipes are almost always destroyed by pitting

6. *Journal of the Franklin Institute*, Vol. 172, pp. 295.

rather than by the amount of iron lost, a satisfactory means of preventing pitting would be of great value. The remedy most commonly suggested is the use of a more homogeneous iron. Without doubt this would reduce the corrosion due to local galvanic action, but the above experiments indicate that pitting of buried iron is very largely influenced by the nature of the electrolyte in the soil.

It may seem that for comparing the effects of different chemicals, quantities which are chemically equivalent should be chosen. A glance at columns 5 and 8 will show that in a number of cases practically equal corrosion efficiencies occur when the chemical values are very different. Indeed, so far as the tables go, there seems to be no relation between chemical values and corrosion efficiency.

It appears from these experiments that solutions which produce passivity when iron is immersed in them do not protect the iron against electrolytic corrosion when the solutions are in earth, and with the exception of the chromates, no chemicals here tried are of marked value in reducing corrosion. Also the action of iron in solutions is not a safe criterion of its behavior when the iron is made anode in earth containing these solutions.

9. *Efficiency of Corrosion in Soils from Different Sources.* While the foregoing experiments show the effect of the different factors which influence electrolytic corrosion in soils, they naturally raise the question to what extent these various factors are acting in the case of iron pipes subjected to electrolysis under practical conditions. This question seems to be best answered by actually carrying out experiments on electrolytic corrosion in a great variety of soils of different kinds, and gathered from widely different sources, at the same time maintaining the conditions as near to practical conditions as possible. In order to do this, corrosion tests were made on a large number of samples of soils which were gathered from various cities and sent to the Bureau of Standards at Washington for test as to their various physical properties. Ninety-seven such samples were used for these corrosion tests, which were taken from various places in Philadelphia, Pittsburgh, Erie and Apollo, Pa., St. Louis, Mo., Butte, Mont., and Albuquerque, New Mexico. Practically all of these soil samples were taken from excavations made for the purpose of examining pipes and were taken at about the same depth as the pipe in most instances. In all cases the samples were put at once into hermetically sealed cans

and kept therein until ready for test. For the purpose of making the corrosion tests, the soils were divided into two classes. Those soils from Philadelphia, St. Louis, Butte and Albuquerque were saturated with distilled water and kept so throughout the tests. The current density of the discharge averaged about 0.0002 ampere per square centimeter. The soils from Pittsburgh, Erie and Apollo, Pa., were tested with the same moisture content which they had when taken from the ground, and the current density was maintained at about 0.001 ampere per square centimeter. We thus have for one set a very wet soil and a rather low current density and in the other a rather high current density with what may be considered as roughly average moisture content, since at the time the samples were taken the soil was neither unusually wet nor unusually dry. The results of these efficiency of corrosion tests are given in Table IX. An examination of specimens 1 to 85, in which the earth was very wet and the current density low, shows quite high efficiencies of corrosion, the extreme ranges being 87.9 per cent for specimen No. 2 and 126.3 per cent for No. 30. All but two show values exceeding 100 per cent, while the great majority fall between 100 per cent and 115 per cent, the average of all being about 107 per cent.

The figures in the second group show much lower values, the extreme range being between 36.3 per cent and 104.3 per cent. Most of the values fall between 60 and 100 per cent, with an average for all specimens of about 76 per cent. The difference between the efficiencies of corrosion shown by the two series is evidently due partly to the lower moisture content and higher current density in the latter case. These results are in accord with the data already presented in which the effects of moisture and current density have been studied separately. It should be pointed out here that while the current density in the second series is higher than may be expected under average conditions in practise, it is no higher than would frequently be encountered under moderately severe practical conditions. From these and the preceding tests it will be evident that under average practical conditions we may expect the corrosion efficiency to be of the order of 100 per cent when the earth is very wet and the current density quite low, while as the moisture content is reduced or the current density increased, the corrosion efficiency falls off and will usually be found to range between 50 and 110 per cent, while in quite dry soils, such as might at times be encountered in prac-

TABLE IX

CORROSION EFFICIENCY TESTS ON SOILS FROM DIFFERENT SOURCES

A

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
1	2.294 g.	0.114 g.	2.180 g.	1.867 g.	116.8
2	1.811	0.170	1.641		87.9
3	2.147	0.062	2.085		111.9
4	2.244	0.195	2.049		110.0
5	2.327	0.090	2.237		119.8
6	2.203	0.117	2.086		112.1
7	2.156	0.075	2.081		111.9
8	2.244	0.175	2.069		111.0
9	2.273	0.089	2.084		116.7
10	2.363	0.133	2.230		118.8
11	1.881	0.064	1.817		97.3
12	2.103	0.174	1.929		103.4
13	2.173	0.126	2.047	1.876	109.2
14	1.992	0.025	1.967		104.8
16	2.584	0.280	2.304		122.8
17	2.186	0.041	2.145		114.4
18	2.207	0.032	2.175		115.9
19	2.052	0.086	1.966		104.8
21	2.058	0.091	1.967		104.8
22	2.187	0.130	2.057	1.871	109.9
23	2.168	0.203	1.965		105.0
24	2.091	0.044	2.047		109.4
26	2.239	0.078	2.261		120.9
27	2.398	0.112	2.286		122.3
29	2.091	0.068	2.023	1.895	107.0
30	2.497	0.108	2.389		126.3
32	2.190	0.044	2.146		103.6
33	2.130	0.079	2.051		108.4
34	2.068	0.061	2.007		106.0
37	2.310	0.170	2.140		113.2
38	2.114	0.097	2.017		106.4
39	2.362	0.085	2.277		102.4
41	2.300	0.025	2.275		120.2
42	2.313	0.155	2.158		113.7
43	2.161	0.150	2.011	1.913	105.0
44	2.148	0.094	2.054		107.3
45	2.202	0.031	2.171		113.4
46	2.105	0.182	1.923		100.7
47	2.257	0.101	2.156		112.8
48	2.489	0.351	2.138		111.7
49	2.126	0.022	2.104		110.2
50	2.177	0.121	2.056		107.3
51	2.188	0.122	2.066		107.9
52	2.305	0.104	2.201		116.1
53	2.200	0.148	2.052		107.3
54	2.250	0.228	2.022		105.7
55	2.108	0.052	2.056		107.4
56	2.330	0.117	2.213		115.6
57	2.252	0.115	2.137		111.7

TABLE IX—Continued

CORROSION EFFICIENCY TESTS ON SOILS FROM DIFFERENT SOURCES

Rod No.	Total loss	Self-corrosion	Electrical loss	Theoretical loss	Corrosion efficiency
58	2.206	0.156	2.050		107.2
59	2.258	0.247	2.011		105.2
60	2.194	0.133	2.061		107.8
62	1.318	0.054	1.264		66.2
63	2.201	0.143	2.058		107.6
64	2.242	0.068	2.174	1.866	117.2
65	2.224	0.157	2.067		116.3
66	2.295	0.060	2.235		121.0
67	2.085	0.045	2.040		109.9
68	2.164	0.060	2.104		113.4
69	2.276	0.181	2.095		112.9
71	2.225	0.096	2.129		114.7
72	2.210	0.156	2.054		110.8
73	2.152	0.020	2.132		104.9
74	2.070	0.096	1.974		106.4
75	2.190	0.100	2.090		112.6
76	2.062	0.038	2.024		109.2
77	2.200	0.072	2.128		114.6
78	2.089	0.151	1.938		104.4
79	2.063	0.114	1.949		105.1
81	2.286	0.064	2.222		119.8
82	2.152	0.157	1.995		107.5
83	2.330	0.135	2.195		108.3
84	1.706	0.188	1.518		81.8
85	2.062	0.003	2.059		111.0
	B—Pittsburgh, Pennsylvania, Soils*				
	4.600	0.207	4.393	4.97	88.4
	5.100	0.177	4.923		99.2
	3.953	0.295	3.658		74.7
	2.780	0.220	2.560		51.6
	5.210	0.030	5.180		104.3
	4.368	0.005	4.363		87.8
	5.195	0.140	5.055		101.6
	2.822	0.270	2.552		51.4
	3.005	0.140	2.865		57.7
	4.435	0.145	4.290		86.4
	3.519	0.546	2.973		67.2
	4.272	0.545	3.727		72.0
	C—Erie, Pennsylvania, Soil*				
	4.932	0.185	4.747	4.75	99.9
	3.499	0.250	3.249		68.2
	4.692	0.255	4.437		94.0
	3.595	0.129	3.466		72.9
	4.777	0.245	4.532		74.4
	18.180	1.451	17.729		80.7
	7.531	0.040	7.491		36.3

*Current density, one milliampere per square centimeter.

No. 1 to 37 inclusive taken from Philadelphia. Nos. 38 to 47 taken from Norristown, Pa. Nos. 48 and 49 from Albuquerque N. M. Nos. 50 to 84 from St. Louis, Mo

tise, a much lower figure might occur. We are convinced that under average conditions of soil moisture, and with current densities that may be expected in localities where electrolysis conditions may be considered moderately severe, a corrosion efficiency between 50 and 110 per cent will usually prevail. It will be seen also from the foregoing data that the decrease in corrosion efficiency due to increased current density is by no means as rapid as the increase in current, so that within the limits of current density that will usually be encountered in practise the actual amount of corrosion will be found to increase with increase of current.

The question may well be raised as to the reliability of corrosion efficiency experiments carried on in earths in the laboratory, and the extent to which such results may be considered as representing what would take place in the earth under normal conditions. In general, however, it will appear that experiments made in the laboratory are much more satisfactory for studying the laws of corrosion, because conditions can then be much more readily controlled, and it is simply necessary to determine whether or not the laws of corrosion are substantially the same in the case of experiments on iron imbedded in small samples of soil as they would be if the iron were imbedded in the earth out of doors, all other conditions being the same. This would probably not be true if the experiments were continued over a great length of time during which certain soluble constituents of the soil in the laboratory specimens might become exhausted by the corrosive processes, but we have ample reason to believe that experiments thus made and extending over a comparatively short time represent quite closely what may be expected to take place in the case of pipes under actual conditions. Numerous experiments have been made on specimens of iron imbedded in the earth out of doors in order to check this conclusion and to guard against any serious error that might be introduced by possible conditions of the soil. Some of the data bearing on this have already been given in the earlier part of this report relating to the effects of depth of burial and of current density on efficiency of corrosion, which show that for similar conditions the results for the outdoor tests do not give results materially different from the indoor tests. Another series is given in Table X. In this case a number of specimens of iron were buried in the earth out of doors and caused to carry current for several months, and the efficiency of corrosion was

determined. The current density varied considerably during the experiments, due largely to change in resistance of the soil, but on the whole the range of current density averaged about the mean of the values used in the tests on effect of current density given above. The moisture content, of course, varied considerably from time to time.

An examination of Table X shows that the efficiencies of corrosion in these outdoor tests ranged between approximately the same limits as those carried on indoors for similar ranges of moisture and current density. These data afford additional evidence that the results of the corrosion efficiency experiments carried out on samples of iron imbedded in soils in the laboratory

TABLE X

EFFICIENCY OF CORROSION

SPECIMENS BURIED IN GROUND OUT OF DOORS

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
1	15.719g.	0.286g.	15.433g.	74.9
3	12.153	0.286	11.873	72.8
5	4.425	0.282	4.143	61.5
6	5.879	0.282	5.597	73.9
7	5.894	0.280	5.614	80.0
10	6.374	0.280	6.094	96.3
11	2.364	0.278	2.086	83.3
12	3.310	0.278	3.032	76.8
			Ave.	77.9

are of substantially the same order of magnitude as they would be if the iron had been buried out of doors.

10. *Causes of Variations in Efficiency of Corrosion.* The causes which give rise to corrosion less than the theoretical amount according to Faraday's law have been the subject of much research by numerous investigators in connection with studies of passivity in iron. Numerous theories have been evolved, but comparatively little is definitely known in regard to this subject. The subject is too complicated and would lead to too much theoretical detail for us to go into here. On the other hand, no attention has been given to the influences that may be responsible for corrosion efficiencies greater than 100 per cent, and in view of the frequency with which these high efficiencies of corrosion occur it seems well to present here very

briefly a few comments as to the possible causes that may be responsible for these high values.

It has been seen that the efficiency of corrosion of iron imbedded in earth in many cases exceeds 100 per cent, although we have not been able to confirm the results of other investigators previously referred to in this paper who have reported electrolytic corrosion amounting to several times the theoretical value. The highest values which we have found in our experiments have been of the order of 150 per cent, but for the most part the corrosion has not been greater than 20 per cent in excess of the theoretical amount. The very large number of cases, however, both among the tests already described and among those that follow, in which the corrosion efficiency exceeds 100 per cent, even after careful correction has been made for self-corrosion, indicate quite clearly that the loss of iron due to the discharge of electric current is in many cases appreciably greater than the theoretical amount. This is a matter of great importance and is being given special attention with the view of throwing further light on its causes, but much yet remains to be done before the phenomena can be properly understood.

Several causes suggest themselves as possible factors in producing this high efficiency of corrosion, some of which are discussed below.

a. *The Formation of New Galvanic Couples.* It is well known that when iron corrodes in the presence of water and oxygen, oxides of iron are formed as end products. Under most underground conditions these will be deposited at the surface of the iron in more or less irregular contact with the iron. These oxides are fairly good conductors and are also electro-negative against iron, so that when a particle of iron oxide comes in actual contact with the iron, a galvanic element is formed which tends to corrode the adjacent iron. It seems not improbable, therefore, that when a clean piece of iron is subjected to the discharge of electric current the formation of the iron oxide which results from the initial corrosion may set up galvanic couples which did not before exist and thus greatly increase the self-corrosion on the specimen.

The following experiments were carried out to gain an idea of the effect of the initial corrosion products on subsequent electrolytic corrosion and on the self-corrosion of the specimen. In this experiment, twelve two-quart tin cans were coated outside with paraffin, and a layer of heavy paraffined paper placed

over the sides. The cans were then nearly filled with red clay which had been air-dried two months, and sifted through a 20-mesh sieve; 300 g. of distilled water was added to 700 g. of this sifted earth, and the whole thoroughly mixed before it was packed in the cans. This earth was nearly saturated with water. For anodes and check specimens cylinders of ¼-inch (6.3 mm.) Norway iron, 2 in. (5.08 cm.) long, were used. The cylinders were carefully cleaned and placed vertically in the cans, the anodes in the center and the check specimens close to the side, and carefully shielded from current flow. A small vessel of water was placed within each can to retard evaporation of the moisture in the earth.

The twelve cans were then connected in series on a 115-volt circuit, the cans serving as cathodes. The current was kept practically constant at 10 milliamperes.

At the end of 429 hours, eight cans were removed from the circuit. Four of these were set aside unopened. From the other four the cylinders were removed, cleaned, weighed, and replaced, and the four cans were then replaced in circuit.

At the end of 686 hours more, the cans were opened, the cylinders cleaned, weighed, and the losses computed. When the cylinders were washed in warm water, practically all of the rust came off, so that it was necessary to clean them electrolytically for but a few minutes to obtain a bright surface.

The corrosion of the anodes was more uniform than in most previous experiments, but the corroded surface was somewhat uneven, the loss being greatest near the centers of the cylinders. There was practically no pitting of the check specimens.

The results of the experiments are shown in Table XI. Here the specimens are divided into three groups, *A*, *B*, and *C*. In group *A* the current was kept on the specimens during the first period of 429 hours and then switched off, but the specimens were permitted to stand in the soil undisturbed during the second period of 686 hours, after which they were taken out and weighed and the efficiency of corrosion determined. In this case, if the initial corrosion due to the electric current tended to accelerate self-corrosion, we should expect a higher efficiency of corrosion than if the specimens had been removed as soon as the current was shut off. In group *B* the specimens also carried current during the first 429 hours, but were removed from the earth, cleaned and weighed as soon as the current was shut off and then put back in circuit again. If the self-corrosion is

greater, due to the initial electrolysis, we should expect that the efficiency of corrosion would be smaller for the first period in group *B* than was obtained for group *A*. The table shows that such was the case, although the difference is quite small and

TABLE XI

EFFECT OF INITIAL PRODUCTS ON SUBSEQUENT CORROSION

Area of exposed metal, 7.6 sq. cm. Current density about 1.2 milliamperes per sq. cm. Moisture in soil about 30 per cent.

No.	Total loss	Self-corrosion	Electrical loss	Efficiency of corrosion
		Group A		
2	4.270g.	0.085g.	4.185g.	102.8
6	4.408	0.085	4.323	106.3
7	4.365	0.085	4.280	105.2
12	4.370	0.085	4.285	105.3
			Ave.	104.8
		Group B. 1st Period		
1	4.230	0.045	4.185	102.8
3	4.226	0.045	4.181	102.7
13	4.225	0.045	4.180	102.7
14	4.273	0.045	4.228	103.8
			Ave.	103.0
		Second period		
1	6.316	0.080	6.236	87.8
3	6.645	0.080	6.565	92.5
13	6.475	0.080	6.395	90.1
14	6.823	0.080	6.743	95.0
			Ave.	91.4
		Group C		
4	11.185	0.149	11.036	99.0
5	10.658	0.149	10.509	94.3
8	10.275	0.149	10.126	90.8
9	10.945	0.149	10.796	96.9
			Ave.	95.2

may possibly be due to other causes. By cleaning these specimens and putting them back in the same soil in which they had previously run and maintaining the same current flow as before during the second period we could determine whether there was

any marked change in the efficiency of corrosion due to changes in the soil caused by the flow of current. The table shows that there was a marked difference here, the efficiency of corrosion being much lower during the second period than during the first. In group *C* the specimens were permitted to remain in circuit during both the first and second periods without interruption.

In comparing the results obtained from these three groups it is significant that the highest apparent efficiency of corrosion was obtained when the current was allowed to flow for a time and then removed and the specimen allowed to remain in the earth subjected to the action of self-corrosion during the second period. The next largest apparent efficiency was obtained when the specimens were cleaned and weighed at the end of the first period immediately after the stopping of the current. The lowest efficiency was obtained when the cleaned specimens of group *B* were returned to the same earth which had been previously used and again connected in circuit during the second period. Further, group *C*, which ran continually throughout the first and second periods, showed an intermediate value of corrosion efficiency. These results appear to show that there are two opposing tendencies at work, one of which is to increase the corrosion efficiency as in group *A*, due to some cause associated with the flow of current, and the other a tendency to decrease the corrosion efficiency as in group *C*, due perhaps to depletion of certain ingredients in the electrolyte. Other experimental data given in this paper indicate that this tendency for the efficiency of corrosion to decrease with time may be due either to the exhaustion of dissolved oxygen or to a loss of moisture by the earth.

The check specimens used in these experiments also show the effect of current flow on the self-corrosion of check specimens placed in the cans along with the anodes. Examining the data for group *B* under the column headed "Self-corrosion", we find that during the first period the rate of corrosion was less than after the check specimens had been cleaned and returned to the same cans. By comparing the self-corrosion in group *A* with those in groups *B* and *C*, the tendency is seen to be the same and even more marked. Further, by comparing the self-corrosion of group *B* with that of group *C* we find that, although the total flow of current is the same, the corrosion is considerably greater in the latter. Since those of group *B* were removed once and

cleaned, while those of group *C* were not, this result seems to support the theory that the presence of a small amount of initial corrosion tends to stimulate the self-corrosion throughout the remaining period of the test. It should be borne in mind, however, that the figures on which this statement is based are subject to such large variations that they should not be accepted as conclusive until they have been repeatedly verified.

b. *The Depolarizing Effect of Oxygen.* According to the electrolytic theory of corrosion all iron contains sufficient differences in physical or chemical structure at different points on its surface to set up local galvanic elements which are supposed to be responsible for self-corrosion. Under ordinary conditions of self-corrosion, therefore, there will be certain points on the surface which will be anode points discharging current into the electrolyte and corroding the iron and there will also be, near by, cathode points at which the current reenters the iron. The amount of corrosion which results from these couples will, of course, depend upon the resistance of the local circuit as well as on the effective difference of potential which exists between adjacent points. When current flows in these local paths there is a tendency to form a film of hydrogen at the cathode points which diffuses but slowly, and this not only sets up a counter electromotive force but it likewise introduces a large amount of additional resistance into the local circuit. In consequence of this the self-corrosion may be said to inhibit itself to a very considerable extent. If now we superpose on this specimen an electric current, making the specimen anode, more or less oxygen will be liberated near the surface of the metal which may react with the hydrogen, thus in effect depolarizing the local galvanic action and permitting much greater self-corrosion in the case of a specimen discharging current than in a case of a similar specimen not discharging. This excess of self-corrosion would always appear, due to the main current flowing, and would thus increase the apparent efficiency of corrosion. It is easy to see how this effect could increase the efficiency of corrosion from a low value up toward 100 per cent, although it would not in general tend to make the corrosion efficiency greater than 100 per cent.

c. *Non-Uniform Corrosion of the Iron.* When iron corrodes it is always with greater or less irregularity. Pits may be formed in which a small hole on the surface may communicate with a large chamber below, and this pitting may pursue such an

irregular course as to eat entirely around particles of iron, causing them to fall away from the test specimen. This seems particularly likely to happen in the case of very impure metals, which often exhibit a more or less honeycombed aspect after long-continued corrosion. Since the efficiency of corrosion is always determined from the net loss of weight, any particles of iron that might be dislodged in this manner would be charged against the current and in this way the corrosion efficiency might easily be made to appear larger than 100 per cent.

d. *Circulation of the Electrolyte.* It is well known that if the electrolyte surrounding a piece of iron be kept in constant circulation the amount of self-corrosion which results will be greater than if the electrolyte remains practically still. When an electric current flows through an electrolyte it causes a migration of the ions which may increase the self-corrosion of the iron in a manner analogous to circulation of the electrolyte. Particularly, in the case of an anode there is a tendency for the acid radicals such as Cl, SO_4, etc., to concentrate near the anode surface and it is well known that liquids containing large amounts of these radicals, particularly the chlorine, produce very rapid corrosion of the iron. Here again any excess of self-corrosion which would be produced would be charged against the electric current and a high efficiency of corrosion would result. It is not improbable that any or all of the above-mentioned causes may be operating in certain cases to produce a high efficiency of corrosion. However that may be, it has been definitely established that if a check specimen is imbedded in the earth along with the anode the self-corrosion will always be much higher than if the check specimen is imbedded in the same earth but in a separate vessel. This is true even when ample precautions are taken to shield the check specimens from the flow of electric current. This is shown by the following series of experiments, which is typical of a great many which have been carried out. The anodes were buried in the center of a quart tin can filled with earth, the can itself serving as the cathode. The check specimen was placed in the earth near the cathode and shielded from current flow by means of a glass shield semicylindrical in form and of considerably greater diameter and length than the check specimen. The arrangement is shown in Fig. 1. In many of these experiments, in addition to the check specimens placed inside the can, a second check specimen was also placed in the same kind of earth with the same moisture

content, but placed in a separate vessel through which no current passed. A few of these data, which are typical of all, are given in Table XII.

From this table it will be seen that the average self-corrosion on the check specimens placed in the can carrying current was roughly 2.7 times that on the specimens in the cans through which no current passed, while the time in the latter case was 1.7 times that in the former, thus making the average rate of self-corrosion about 4.6 times as great in the can carrying current as in the one which carried no current. Further, it seems altogether probable from the foregoing discussion of causes of increased corrosion efficiency that the self-corrosion on the anode itself would be considerably greater than that on the check

TABLE XII

EFFECT OF CURRENT FLOW ON SELF-CORROSION

Check No.	Loss of check with iron carrying current 49 days	Loss of check in separate vessel 83 days
7	0.075 g.	0.041 g.
14	0.025	0.022
21	0.091	0.025
28	0.038	0.022
35	0.048	0.045
42	0.155	0.057
63	0.143	0.063
83	0.135	0.018
84	0.118	0.014
Ave.	0.092	0.034

specimen placed inside the same can, so that even though the electrolytic corrosion proper were to take place strictly in accordance with Faraday's law we should nevertheless obtain an experimental result indicating an efficiency considerably greater than 100 per cent.

In view of the foregoing, therefore, it does not appear that we have any reason to suppose that the electrolytic corrosion proper does not take place in accordance with Faraday's law, even though a corrosion efficiency of much more than 100 per cent is indicated. Nevertheless in computing corrosion efficiency it is proper to charge all of this excess of self-corrosion against the electric current, since in the absence of the current it would not have occurred, and the corrosion directly chargeable to the current includes all of that which results from the passage of

the current, whether due directly to the current or to secondary causes brought into action by the current flow.

11. *Effect of Very Low Voltage.* In all of the foregoing experiments, although the current density has often been reduced to quite low values, the voltage impressed upon each pair of electrodes has in general been somewhat high, being of the order of several volts in most instances. This has been due to the fact that the small size of most of the electrodes used gave rise to so high a resistance in the earth that voltages of this order were necessary in order to produce the desired current density. Although there is no theoretical reason why the efficiency of corrosion should vary with voltage except in so far as it affects the current density, nevertheless it seemed very desirable to carry out a few experiments on very low voltages, particularly below one volt, in order to determine whether the efficiency of corrosion would be materially different with such extremely low voltages from what it is on the higher values. Accordingly, three cells were made up, using tap water as an electrolyte and thin sheet iron electrodes separated by several sheets of filter paper. This gave a very low resistance between the electrodes and made it possible to secure sufficiently large current on much lower voltages than had been possible in the case of specimens buried in soil. One of these cells was run on a constant potential of 0.1 volt, another on 0.6 volt, and the third at one volt. Current measurements were made at frequent intervals and the ampere-hours determined. The results are shown in Table XIII. It will be seen by reference to this table that the efficiencies of corrosion are comparatively high, being highest in the case of the one-volt cell and lowest in the case of the 0.6-volt cell, and intermediate in the case of the 0.1-volt cell. The current densities are given in the table and are seen to be extremely low, the lowest being but 0.003 of an milliampere per square centimeter. These results show quite clearly that there is no reason to expect that the corrosion efficiency changes materially at any critical value of voltage within a range that is of any practical consequence in the negative return of street railway systems.

II. EARTH RESISTANCE

The foregoing experiments show what may in general be expected under different conditions as to the discharge of current from iron electrodes buried in soils. In practise, however,

when investigating electrolysis conditions, we are not dealing with known conditions of current flow, since it is in most cases impracticable to measure directly leakage currents at any point in the soil without resorting to measures that are too tedious and expensive for most work. We have, on the contrary, certain easily determined voltage conditions throughout the negative railway return system, and hence, in order properly to interpret the data above presented relating to laws of corrosion, it is necessary to take into consideration the effect of earth resistance on the stray currents that may be carried by the pipes and discharged by them into the earth under known conditions as to potential differences in the network. It is not the purpose of this paper to go into detail in regard to the matter of earth resistance, as this is to be treated somewhat fully in another

TABLE XIII

LOW VOLTAGE TEST

Plate No.	Loss total	Electrical loss	Theoretical loss	Corrosion efficiency	Current density milliamp. per sq. cm.	Voltage
1	0.498 g.	0.456 g.	0.467 g.	97.7	0.051	1.0
2	0.153	0.113	0.127	89.0	0.014	0.6
3	0.062	0.022	0.024	91.7	0.003	0.1

Area of anode, 47.47 sq. cm.
Ave. natural loss of anode 40 mg.

paper by the authors in a publication of the Bureau of Standards. The great importance of the subject of earth resistance, however, in relation to electrolytic corrosion in soils, makes it desirable to present here very briefly a few fundamental principles in regard to the resistance of soils and its relation to stray current electrolysis.

It is obvious that if the soil surrounding the pipe network possessed infinite resistance, there would be no trouble from electrolysis, since in that case no stray currents could leak from the tracks and hence find their way into the pipe. On the other hand, if the earth possessed zero resistance, we would also have no electrolysis, since in that case the earth would short-circuit the pipes and prevent them from taking up the stray currents. Somewhere between these two extremes we will obviously have a value of earth resistance which, in any given case, would pro-

duce a maximum of electrolysis trouble. The value of this resistance required to give a maximum electrolysis undoubtedly varies greatly with conditions; such as geometrical form of the pipe and track networks, kinds of joints used in pipes, size of pipes, resistance of rail return, and numerous other factors. We feel confident, however, from observations made under practical conditions, that in most, if not all cases, the resistance of the earth will be found much higher than that required to produce maximum electrolysis, so that in general we may expect the electrolysis to be greater the lower the resistance of the earth. With a view of giving an idea of what may be expected in the way of earth resistance in practise, we present below a summary of some investigations which we have made in regard to variation of earth resistance with varying conditions, and following that we have given the results of a considerable number of earth resistance measurements made on a variety of soils taken from widely scattered sources. In making these earth resistance measurements several different methods were used, in some of which the earth was measured in place without being disturbed, while in other cases the samples were taken to the laboratory, packed in glass cylinders and the resistance measured between plastic amalgam electrodes pasted on the ends of the cylinder, the voltmeter-ammeter method with alternating current being used. In a good many cases both methods were used and the results were found to check in a very satisfactory manner. In making the earth resistance measurements in place, two excavations were made side by side to a depth of several feet, leaving a portion of undisturbed earth several inches in thickness between the two excavations. The sides on this undisturbed portion were made approximately parallel and fairly smooth, and small electrodes a few inches in diameter placed on the opposite sides. These electrodes were then surrounded by guard rings of sufficient diameter to assure practically parallel lines of current flow between the two electrodes. The resistance of the earth between the electrodes was then measured by means of voltmeter-ammeter methods as in the laboratory, alternating current being used for the purpose. In making these measurements care was taken to keep the electrodes and the guard ring not only at the same potential, but also to see that there was no displacement of phase between the e.m.fs. applied to them.

In making the tests in the laboratory, preliminary experiments showed that much more satisfactory results could be obtained

by compressing the earth in the testing machine to such a point that further increase in pressure caused practically no variation of resistance. It was found, and will be shown by the curves below, that with increase of pressure a point is soon reached beyond which the resistance varies but slightly with further increase in pressure. Careful comparison of results obtained by first measuring the resistance in place, in the ground, and later in the same earth in the laboratory, indicated that they were practically the same whichever method was used, and since the method of measuring the resistance in the laboratory was so much more rapid and convenient, this method was used for the great majority of measurements that are presented below.

12. *Effect of Moisture Content on Earth Resistance.* Moisture content is one of the controlling factors in earth resistance. In Table XIV is given a series of resistance measurements taken on a

TABLE XIV

RELATION BETWEEN THE AMOUNT OF MOISTURE IN THE SOIL AND ITS SPECIFIC RESISTANCE

Per cent moisture (in terms of dry earth)	Specific resistance ohms per centimeter cube
5.0	2,340,000
11.1	237,400
16.7	12,880
22.2	6,835
33.3	5,400
44.5	4,725
55.6	4,870
56.7	5,197
77.8	5,045

sample of red clay soil with varying moisture content, which may be regarded as more or less typical. For making each measurement a new sample of thoroughly dry earth, dried at 105 deg. cent., was taken and the required amount of moisture added, the percentage of moisture being expressed in terms of the dry earth. It will be seen that above about 22 per cent of moisture the resistance remains practically constant, but below this value, the resistance rises very abruptly with decrease of moisture content, and at 5 per cent of moisture the resistance has risen to considerably over four hundred times its value when the soil is saturated. This shows that the actual current flow to and from a pipe imbedded in soil is dependent in vastly greater degree on the moisture content than on the potential difference between the pipe and surrounding structure, and points to the fact that a potential difference which might be

perfectly safe in a high and well drained locality might be sufficient to give rise to a great deal of damage in a low and damp locality. This tendency has of course been well recognized, but it has not been given the consideration which it deserves. Cases frequently arise in which this fact might well be treated as an important factor in determining the location of a railway substation, and particularly the points at which insulated radial return feeders might best be connected to the tracks.

Another important practical aspect of this change in resistance with moisture content is its effect on the distribution of potential drops throughout the negative railway return area. Since the various parts of the pipe system are buried at different depths and are very irregularly located with respect to the tracks, it is evident that changes in the moisture content with depth will exert a marked influence on the distribution of the resistance in the path of the leakage current, which in turn will greatly affect both the magnitude and distribution of the potential gradients throughout the system. For this reason not as much reliance should be placed on voltage surveys made at extremely wet and more especially at very dry periods as on those taken under more nearly average moisture conditions.

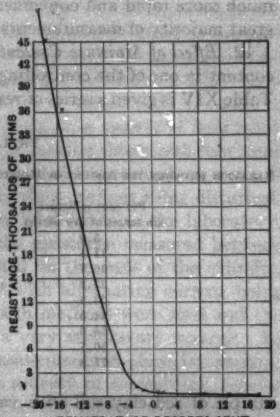


FIG. 8—RESISTANCE-TEMPERATURE CURVE

13. *Effect of Temperature on Earth Resistance.* The effect of temperature on the resistance of soil was determined throughout the range from about 18 deg. cent. to − 18 deg. cent. (0 to 65 deg. fahr.). For this purpose a moist soil was used and was placed in a vessel surrounded by an ice-chamber in which a mixture of ice and salt was placed and the whole was allowed to stand until the temperature had reached about − 18 deg. cent., the resistance being measured from time to time by means of electrodes which were imbedded in the sample of earth and rubber-covered leads brought out. The temperature of the

earth was taken at the same time each resistance measurement was made, an ordinary mercury thermometer inserted in the center of a hollow electrode being used. The results of these resistance measurements, as a function of temperature, are given in Table XV and are plotted in Fig. 8. By reference to the curve it will be seen that the resistance varies throughout very extreme ranges, even within the ranges of temperature variation that commonly occur in this country. Above freezing, the resistance variation is much less marked, but even here we find that the resistance at zero deg. cent. is approximately 2½ times its value at 18 deg. cent. At about the point at which the soil water begins to freeze there is tremendous increase in the temperature coefficient of resistance, and as the temperature becomes lower the resistance rises enormously, and at − 18 deg. cent. the resistance is seen to be over two hundred times as great as at 18 deg. above zero.

TABLE XV

EFFECT OF TEMPERATURE ON RESISTANCE OF SOIL

Soil No. 32. Moisture 18.6 per cent. Specific resistance at 20 deg. cent. 6260 ohms per cu. cm.

Temperature cent.	Resistance ohms
18.0	224
13.0	286
8.5	398
1.5	458
1.0	462
0.0	542
− 2.0	940
− 3.0	1,185
− 5.5	4,340
−12.0	21,700
−13.0	24,600
−15.0	36,200
−18.0	45,000
−19.0	48,900

This enormous variation of earth resistance with temperature is of considerable practical importance and indicates that in moderately cold weather such as prevails in the northern cities, comparatively little trouble from electrolysis may be expected. This is not due primarily to the higher resistance of the earth immediately surrounding the pipes, since the pipes are usually located at a sufficient depth so that the temperature of the earth immediately surrounding will not reach the lower values

used in this experiment. The real reason for the diminution of electrolysis trouble with the fall in temperature is the reduction of leakage current from the rails. It will be evident that when the ground is frozen even but a few inches deep, the resistance of the earth immediately surrounding the rail becomes enormously increased, and the leakage of stray currents into the earth is thereby correspondingly reduced. And since the rise in resistance with even a few degrees of frost may be many fold, it is apparent that but a thin layer of frozen earth about the rail would be necessary in order to produce a very marked increase

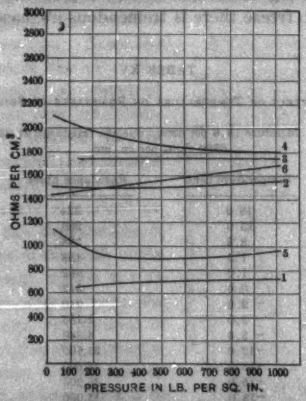


FIG. 9—SPECIFIC RESISTANCE-PRESSURE CURVES OF EARTH

1—Blue clay, sample 51; 2—black humus, sample 52; 3—black humus, sample 59; 4—yellow clay, sample 56; 5—sand and humus, sample 64; 6—yellow clay and sand, sample 83.

in the total resistance of the path of the leakage current. This reduction in electrolysis troubles in cold weather due to increase in resistance of the earth is further augmented by the increase of the conductivity of the rail return which takes place at the lower temperature, which may amount to as much as 15 or 20 per cent, and is sufficient, as a rule, to compensate for the increased load which usually prevails during the cold period.

It should also be pointed out here that the effect of variations in temperature with depth on the resistance of earth will have an effect on the distribution of potential gradients in the earth very

similar to variations in moisture content referred to above. For this reason it is preferable not to make voltage surveys at times when extremely low temperatures prevail.

14. *Effect of Mechanical Pressure on Earth Resistance.* Of considerable interest, although of much less practical importance, is the effect of mechanical pressure on the electrical resistance of earth. As already stated, when pressure is applied to a sample of earth its resistance is but little affected as a rule, after a certain relatively low value of pressure is reached. This is shown in Fig. 9, which gives resistance-pressure curves for a number of different soils from various sources. The range of pressures here is for the most part between twenty and one thousand pounds per square inch, and the variations in resistance between these limits are surprisingly small. Numerous measurements of the resistance of earth two or three feet below the surface before being disturbed, using the guard ring method, and subsequent measurements of the same earth in the laboratory, under pressure, show that the resistance at a few hundred pounds pressure per square inch is substantially the same as that of the undisturbed earth.

15. *Other Factors Affecting Current Flow.* There are other factors also which affect the resistance of soils, such as its mechanical properties, and chemical constituents, and these may have an important bearing on current flow to and from the buried pipes. The character of the street railway roadbed is also an important factor in determining the extent of leakage of stray current into the earth. A well-drained rock or concrete roadbed may in general be expected to offer much higher resistance to the leakage of current than one in which the construction is such that a large amount of moisture is retained. Polarization and film resistances at the surface of the pipes may also be an important factor in current flow. As soon as an electromotive force is applied to a buried pipe the current flow drops off rapidly with time, especially during the first few minutes, due to the setting up of counter e.m.fs. and the formation of film resistances. The extent to which this may occur in some cases is shown in Fig. 10, which shows the effective resistance as a function of time after the application of an e.m.f. of about six volts between two short lengths of cast iron pipe buried about twelve feet apart. From this it will be seen that the initial resistance of about 18 ohms has practically doubled within half an hour after the e.m.f. is applied, and after

that the resistance remains practically constant. In this case the effect of the polarization and film resistance is practically as great as the total soil resistance between the pipes. These results were obtained when the soil was very wet, and it is probable that in a comparatively dry soil the effect would have been less marked.

16. *Resistance of Soils from Different Sources.* In order to give an idea of the order of magnitude of the resistances that may be expected in practise, together with the range of variation of the same, we give herewith a table of resistances of soils taken from various points in the cities of Philadelphia and St. Louis and other cities. In all of these the specific resistance of the soil is measured with the same moisture content which it had when first taken from the ground and all were measured at about one temperature.

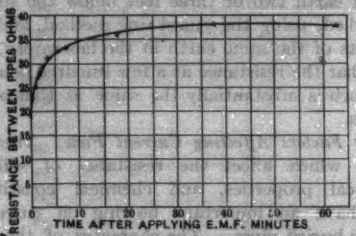


FIG. 10—EFFECT OF POLARIZATION ON RESISTANCE BETWEEN BURIED PIPES

The soils from each city were taken from widely scattered points and represent a wide variety of different kinds of soils, as will be evident from the brief description. The moisture content was determined in each case and is given along with the other data. The results are shown in Table XVI. An examination of this table reveals some striking differences in two particulars: In the first place the specific resistances found in St. Louis shows a much greater degree of uniformity than those found in Philadelphia. The extreme range of values of specific resistance for St. Louis earths is between 400 and 1800 ohms per centimeter cube, while for Philadelphia the range is between 595 and 610,000 ohms per centimeter cube. The other chief point of difference is the magnitude of the mean value of resistance, the average value of the specific resistance for all the samples taken in St. Louis being 1053 ohms, while the average for the Philadelphia

TABLE XVI

SPECIFIC RESISTANCE OF SOILS

No.	Character	Per cent moisture	Ohms per cu. cm. Spec. resistance
	PHILADELPHIA SOILS		
1	Moist gray clay	11.7	651
2	" yellow clay	14.8	3,850
3	" blue clay	16.1	3,036
4	Nearly dry red sand	7.6	2,700
5	Moist red clay	17.4	8,820
6	Nearly dry mica schist	4.7	156,400
7	Nearly dry gray clay	16.2	5,930
8	" " clay, rock and cinders	17.9	595
9	Moist blue clay and gravel	13.1	2,830
10	Moist blue clay	15.3	1,605
11	Moist yellow clay	17.2	5,340
12	Moist yellow clay and sand	13.4	6,280
13	Wet gravel	11.0	24,550
14	Wet humus and clay	9.5	2,600
15	Moist clay, sand, cinders	17.4	2,080
16	Damp, disintegrated schist	12.9	12,100
17	Wet clay, cinders, gravel	16.9	5,000
18	Moist yellow clay	19.4	4,825
19	Moist yellow clay	17.3	3,820
20	Moist red clay	19.3	21,200
21	Moist yellow clay	15.6	25,900
22	" red sand and clay	15.7	13,700
23	" clay, cinders, sand	13.7	1,494
24	" clay and sand	20.0	821
25	Moist clay and sand	18.7	1,774
26	Damp clay and humus	16.7	2,490
27	Damp clay and humus	16.2	2,585
28	Nearly dry disintegrated schist	0.3	610,000
29	Damp yellow clay	16.8	2,250
30	Moist yellow clay	18.5	2,455
31	Saturated clay and cinders	23.8	4,410
32	Moist clay and sand	18.6	6,260
	ST. LOUIS SOILS		
50	Wet clay	20.4	600
51	Blue clay	21.1	700
52	Moist virgin soil	20.8	1,500
53	" yellow clay	21.5	1,250
54	Yellow clay	19.0	1,800
55	Yellow clay		1,600
56	" "	21.1	1,800
57	" "	22.8	1,400
58	Yellow clay	21.3	1,400
59	Virgin black soil	21.2	1,700
60	Yellow clay	16.0	1,800
61	Yellow clay	23.4	990
62	Yellow clay	18.4	700
63	Yellow clay	21.9	950
64	Sand and humus	17.8	925
65	Sand and humus	20.0	900
66	Blue clay	22.0	470
67	Virgin yellow clay	19.1	1,450
68	Virgin yellow clay	22.5	484

TABLE XVI—Continued

SPECIFIC RESISTANCE OF SOILS

No.	Character	Per cent moisture	Ohms per cu. cm. Spec. resistance
69	Yellow clay	22.0	700
70	Virgin yellow clay	20.0	1,700
71	Virgin soil	22.9	840
72	Yellow clay	23.3	900
73	Blue clay	26.1	400
74	Blue clay	19.1	600
75	Blue clay	24.2	830
76	Moist blue clay	23.1	500
77	Nearly dry yellow clay	16.4	1,100
78	Blue clay	17.1	650
79	Yellow and blue clay	26.9	600
80	Yellow and blue clay	19.7	820
81	Blue clay	20.0	750
82	Clay and loam	19.2	1,450
83	Sandy clay	19.5	1,600
84	Yellow clay	22.6	1,900
	PITTSBURGH SOILS		
33	Damp sand	13.4	4,506
34	Moist yellow clay	16.5	2,819
35	Moist clay and humus	20.5	2,300
36	Blue clay	26.5	14,025
37	Moist gray clay	26.3	619
38	Damp sand	13.0	1,335
39	Damp sand	10.2	8,709
40	Loam and cinders	21.8	1,074
41	Nearly dry sand	12.3	2,908
	ERIE SOILS		
42	Moist clay and gravel	6.0	18,080
43	Clay, coal and gravel	16.7	1,796
44	Wet blue clay	19.3	3,779
45	Moist blue clay and sand	11.9	3,080
46	Moist gravel	5.7	14,025
47	Wet blue clay and sand	19.6	2,462
	APOLLO, PA., SOILS		
48		30.5	1,796
	ALBUQUERQUE, N.M., SOILS		
85		15.3	43,960
86		11.1	59,475
87		11.9	41,908
	WASHINGTON, D. C., SOILS		
88	Air dry red clay	4	2,340,000
89	Nearly dry red clay	10	14,660
90	Moist loam	20	8,720
91	Wet yellow clay and sand	30	41,490
92	Wet humus clay and sand	30	24,060

samples was 28,750 ohms per centimeter cube, the latter being over 27.3 times the former. It should be noted however, in making this comparison, that the high average for Philadelphia is due to a large extent to the abnormally high resistance of two samples containing large quantities of mica, one of which had a specific resistance of 156,400 ohms and the other 610,000 ohms. If these two are eliminated the remaining 31 specimens show an average for Philadelphia of 5885 ohms per centimeter cube, which, however, is still over 5.6 times the value for St. Louis. It is quite probable that this difference is such as to prove an important factor in the electrolysis situation in the two places.

CONCLUSIONS

The following are some of the more general conclusions that may be drawn from the experimental data presented in this paper:

1. The current density has a marked effect on efficiency of corrosion of iron in soils, the efficiency of corrosion being in general greater, the lower the current density. In saturated soils the corrosion may vary between 20 per cent and about 140 per cent for the range of current densities between 5 milliamperes and 0.05 milliampere per square centimeter.

2. Moisture content in the soil also has a marked effect on efficiency of corrosion, the corrosion efficiency being in general greater with increasing moisture content, up to saturation of the soil. Beyond this point increased moisture content has comparatively little effect.

3. Temperature changes within the limits commonly met with in practise have no important effect on corrosion efficiency.

4. The depth of burial of pipes has no direct effect on corrosion efficiency, provided other conditions remain constant. In practise, however, the moisture content, current carried by the pipes, and various other factors which affect corrosion efficiency will vary with depth, so that indirectly differences due to depth may be noted.

5. The amount of oxygen present has no appreciable effect on the efficiency of corrosion, in the case of iron immersed in liquid electrolyte.

6. Corrosion efficiency of iron imbedded in earth is always greater in open vessels than in sealed vessels.

7. The amount of oxygen present has a marked effect on the end products of corrosion. If the corrosion is rapid and the supply of oxygen small, there will be a preponderance of magnetic

oxide, while if the rate of corrosion is low and the supply of oxygen abundant the ferric oxide will predominate. Owing to the fact that the supply of oxygen around pipes buried in earth is always more or less limited, the character of the oxides formed gives some indication as to the rate of corrosion, and thus indirectly as to the cause of the corrosion, if local conditions are properly considered.

8. There is no material difference in the efficiency of corrosion shown by the various kinds of iron commonly used in the manufacture of underground pipes.

9. The fact that a given chemical tends strongly to inhibit either self-corrosion or electrolytic corrosion in liquids is no indication that it will materially retard electrolysis of iron imbedded in soils.

10. Pitting of iron imbedded in soils is affected not only by a non-homogeneous condition of the iron or soil, but also by the chemicals contained in the soil.

11. The efficiency of corrosion was found not to be a function of the voltage except in so far as the current density may be affected. Voltages as low as 0.1 and 0.6 volts showed practically the same efficiency of corrosion as 5 to 10 volts or higher.

12. Corrosion tests on a large number of different kinds of soil from widely different sources, with average moisture content and moderate current density, indicate that corrosion efficiencies between 50 and 110 per cent may usually be expected under most practical conditions.

13. The resistance of soils varies throughout a very wide range with variations in moisture content, the resistance of the comparatively dry soil being of the order of several hundred times the resistance of the same soil at about saturation. Above saturation, increase in moisture content has but little effect on the resistance of the soil.

14. Because of the great variations in resistance of earth with moisture content, voltage surveys should not be made at times when the earth is extremely dry.

15. The resistance of the soils varies greatly with temperature within the ordinary range encountered in practise. In the case of the soils tested, the resistance at 18 deg. below zero cent. was over two hundred times as great as at 18 deg. above zero cent. Even at about freezing temperature the resistance will be several times that at summer temperatures. This not only has an important bearing on the magnitude of the electrolysis

trouble that may occur at different seasons, but it also indicates that, where practicable, voltage surveys should not be made when extremely low temperatures prevail.

16. The experimental results given in this paper have an important bearing on the subject of electrolysis mitigation through the limitation of voltage drop in the negative return. For some years the chief means of preventing trouble from electrolysis in certain foreign countries has been the limitation of the permissible voltage drop between any two points on the return circuit. In some places the limit has been placed on the maximum voltage during peak load, whereas in other cases the average voltage for twenty-four hours has been the determining factor. It will be evident that if the total amount of damage which results is proportional to the average current, then the limitation of the average voltage would be more logical than the limitation of the peak load voltage, since in the former case the cost of meeting the voltage limitation in any given case would be proportionate to the danger involved irrespective of the station load factor; whereas if the voltage at peak load is the determining factor, the cost of complying with the requirements depends not only on the danger involved, but on the load factor of the system, and the poorer the load factor, the greater its cost will be. It appears from the data presented in this paper that the rate of damage does not increase as fast as the voltage increases, because of the tendency toward lower corrosion efficiencies at higher current densities. This indicates that, with a given average all-day current, the actual amount of electrolysis that would occur would be less with a bad load factor than with a good load factor, and hence points to the undesirability of penalizing a high peak of short duration. It would appear very much more logical, therefore, in so far as the damage itself is concerned, to make the average all-day voltage the basis of the limitation, rather than the voltage at time of peak load.

In conclusion, the authors wish to acknowledge their obligation to their colleagues, Mr. O. S. Peters and Dr. H. E. Palmer; to the former for valuable cooperation in the development of the electrolytic method for cleaning anodes which was used throughout this investigation, and also for a large amount of work on the measurement of earth resistances; to the latter for the chemical analyses of soils, and the carrying out of experiments on the effect of oxygen on the end products of corrosion.

DISCUSSION ON "ELECTROLYTIC CORROSION OF IRON IN SOILS" (MCCOLLUM AND LOGAN), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

J. L. R. Hayden: The paper on electrolytic corrosion by Messrs. McCollum and Logan is very interesting for the large amount of data it gives on electrolytic corrosion under actual service conditions, that is, with the iron imbedded in the soil.

The observation that the activity decreases with increasing current density I found very marked in my investigation. I found that under conditions where passivity is possible, complete passivity could be produced by raising the current density, even if only momentarily. Limited time did not allow me to investigate to any great extent the electrolytic corrosion when the circulation of the electrolyte was interfered with by soil or sand, but some experiments showed the same phenomenon observed by the authors, that the "passivating" action is materially decreased by interference with the circulation of the electrolyte. If the passivity is due to the electrolyte in which free hydrogen ions cannot exist, as has been suggested, this phenomenon would easily be explained.

Alexander Maxwell (communicated): We are indebted to Messrs. McCollum and Logan for their excellent paper. The work is noteworthy, not only on account of the range and scope of the data presented, but especially because it is in great measure directly useful, and applicable in connection with field work.

A most important feature of these tests is in the relation between the current density and "efficiency of corrosion." As noted in the paper, the results reported by Ganz in 1912 showed, in general, higher "efficiencies of corrosion" than those found by Messrs. McCollum and Logan; and in the former test the current densities employed were much lower than those used by the authors of the present paper.

The authors have used current densities ranging from 0.03 to 5 milliamperes per square centimeter. It may be interesting to compare these densities with some observed by the writer under actual conditions in city streets.

The following values are calculated from a large number of tests made with Haber's "earth ammeter." These tests were all made in connection with pipes which had actually suffered severe damage by corrosion, and most of the tests were made in places where the current density might be expected to be high, as where only a few feet of soil intervened between the pipe and the rail, and when the pipe was definitely and strongly positive to the rail.

Under these circumstances, it was found that the average apparent current density for areas between 100 and 600 square centimeters, varied from 0.0005 to 0.04 milliamperes per square centimeter. While these measurements were not of great accuracy, I believe that they are dependable as indicating the

general order of magnitude of currents leaving pipe surfaces under the conditions noted above.

It would be interesting to extend the investigation of the variation in corrosion efficiency to very low densities such as those indicated above, for I believe that such densities are more nearly representative of average field conditions, and all of the evidence points towards corrosion considerably in excess of theoretical values, at these low densities.

D. C. Jackson: The authors have brought out in this interesting and useful paper many things that have been previously known, or at any rate supposed to exist, but they have been brought out more clearly in some ways in this paper than heretofore; and they have added materially to the available information on this complex subject. A paper of this kind is one we can wisely listen to, as the electrical enterprises have been too prone to overlook the economic importance of consideration for their neighbors.

Let us see what it means in certain industries if stray-current electrolysis is allowed to proceed. I will for illustration take an art aside from electrical engineering. Take gas, for instance, and consider the case of a gas plant that has an output of 200 million cubic feet per annum. That would be a sufficient gas supply for the needs of a city from 30,000 to 50,000 inhabitants. Suppose the leakage from the mains is doubled from the fairly normal rate of 5 per cent up to 10 per cent, due to the fact that the pipes are fairly rapidly corroded or the joints are affected and it is difficult to keep the pipes tight. Illuminating gas is worth in the Eastern States, delivered at the outlet to the holders, approximately 30 cents a thousand cubic feet, which makes the extra leakage due to electrolysis cost $3000 per year. It costs the company that much to generate and put in the holder the gas lost from the mains on account of their deteriorated condition. Capitalizing that means a good deal of money, in addition to the other various disadvantages that arise from leaky gas mains; and that is for gas mains alone, and leaves out other underground structures. It also makes no allowance for the extra cost of repairs to the mains, which is necessary on account of their leaky character.

If, instead of a little city, in which 200 million cubic feet of gas are sold, we take a large city with a sale of 5000 million cubic feet of gas, under similar conditions of doubling the leakage from 5 per cent to 10 per cent, on account of the corroded mains, and we consider that the gas costs the company at the outlet of the holder 30 cents a thousand, the increased loss of gas becomes a matter of $75,000 a year.

That illustration shows very clearly the problem which Mr. McCollum has been working on, which is of considerable importance. The question is really an economic one. It relates to the expenditure that might be made for protection of underground structures from the ravages of electric railway currents

and the balancing of the annual cost of protection against the annual cost of the injury that the stray currents produce.

Hugh T. Wreaks: I notice that all of the experiments were made on uncoated pipe, and I am curious to know whether future experiments would take in the line of coated pipes, that is, enameled, sherardized or galvanized, because in a recent lecture I attended over in Brooklyn, one of the city engineers described the preparation of their water pipes so as to resist corrosion, and laid great stress on the value of enameled coating; this coating being covered by fairly definite specifications on ductility, strength, melting temperature, etc.

If this has not been touched upon in other papers, I believe it is germane in this discussion.

Harold V. Bozell: Prof. Jackson's mention of gas mains calls to mind a practise in Oklahoma, where usually gas and electric interests in one town are under one ownership and there is mutual interest in looking for solution of the electrolytic problem. I don't know how this has worked in the East, if it has been used, but it was found there that by running gas mains on both sides of the street much less electrolysis resulted; of course the greatest electrolysis occurs in the cross pipes and this was eliminated. It should be stated that paving, access to pipes and other items added to cause the double main system.

Harry Barker: I would like to ask if the soil studies at the Bureau of Standards were carried into alternating-current work. Question continues to arise generally as to the electrolytic effect of alternating current. We would expect of course that where the reversal of the current is rapid, there is little time for secondary chemical reactions to intervene; then on the reversal of the current the original electrochemical reaction itself is reversed. Where the time involved is considerable, the secondary changes may prevent complete reversal. Some experimental results confirming this are available but a wider range is still desirable.

I presume, from the completeness with which the Bureau of Standards has undertaken its corrosion studies, that they must have well considered such points. But the Bureau has said comparatively little about its alternating-current work and, if it would not be publishing the results too early, perhaps Mr. McCollum might add a word on it.

F. C. Caldwell: With regard to the last point in the paper, that is, the limitation of the voltage, I would ask if it is true that it is not wise for a municipality to set a limit to the voltage to be permitted in the tracks, because of the fact that if they do so they are liable to relieve the railway company from responsibility in the matter. That is, if the railway company complies with the requirements of the municipality and keeps its voltage within the prescribed limit, the fact that such limit has been prescribed relieves the railway company from any further responsibility for electrolysis which may take place within that limit.

J. C. Lincoln: I inquire if the authors have any information as to the effect of breaking the pipes, that is, breaking the electrical continuity of the pipes, in lengths of a few hundred feet, or several thousand feet—whether they have any information as to what the effect of such breaking is on the electrolytic effect?

Henry G. Stott: I want to say one word as to the question of the responsibility of the railroad companies, which has been brought up. I would like to remind the gentlemen present that there was a very able paper presented before the Institute some three or four years ago by Mr. George I. Rhodes, which treats this subject very fully, and I think that paper was really a classic on the question of electrolysis, and upon its cure, which is more important. Broadly speaking, the voltage drop in the return circuit has very little to do with the amount of damage, that is my experience. It is more a question of where you lead the current back. By insulating the negative return to the substation or power station, as the case may be, by this method it is possible almost entirely to prevent the leakage of current from the rails to surrounding conducting bodies, and that is the method which the companies with which I am connected have adopted most successfully in some very trying cases.

I simply wish to remind the members who are interested in that subject of the paper written by Mr. Rhodes, as it was one of the clearest expositions on the subject ever presented to the Institute.

Albert F. Ganz: The paper is full of valuable results and conclusions. It describes a very large number of tests made in a laboratory with the accuracy obtainable only in a laboratory, and yet made under conditions exactly resembling those found in every-day practise. Perhaps the most important single result reported is that electrolytic corrosion of iron in ordinary soil, with the low current densities usually met with in practise, follows Faraday's law. This means that under the usual practical conditions met with in electrolytic corrosion of underground iron structures, we can compute the weight of iron corroded on the basis of approximately 20 pounds of iron per ampere-year.

The authors have shown that corrosion efficiency varies with current density, and that with current densities of an order greater than a few milliamperes per square centimeter the corrosion efficiency decreased from 100 per cent to low values with increasing current density. For very low current densities, of the order of a few hundredths of one milliampere per centimeter, they have generally obtained corrosion efficiencies somewhat larger than 100 per cent.

They state that they have not been able to obtain the high efficiencies of corrosion, up to 500 per cent, which I found in some of my tests reported last year. I wish to say in explanation that these high efficiencies of corrosion were obtained only in the tests where the surface scale had not previously been removed

from the test pipe, and where the pipes had only been cleaned to remove dirt and grease. In the tests which I made where the pipes were first turned down in a lathe, removing all surface scale, I obtained efficiencies of corrosion varying between 103 per cent and 123 per cent, which values agree well with those found by the present authors. The very high values found by me were therefore due to the effects of the surface scale.

During the past year I have made a few tests for efficiency of corrosion with soils obtained from several cities, using low current densities of less than one milliampere per square centimeter, with iron anodes cleaned of scale, and I have found values generally somewhat above 100 per cent.

It may be of interest to compute the probable density of current leaving iron pipes in ground and returning to trolley tracks under assumed practical conditions. The resistivity of soil given in the paper varies between 400 and 6000 ohms in a centimeter cube. Assuming a distance of three feet (91 cm.) between a pipe and the rails to which the pipe is positive in potential, the resistance of an intervening column of soil one square centimeter in cross-section would vary between 36,000 and 540,000 ohms. With one volt potential difference there would result a current of from 0.03 to 0.002 milliampere through the column of soil; this corresponds, therefore, to the average density of the current leaving the pipe surface under the assumed conditions for one volt of potential difference. With 5 volts potential difference, a value commonly found in practise, the resultant average current density would vary from 0.15 to 0.010 milliampere per square centimeter.

As to the values of current density which may be considered dangerous to an underground pipe, it should be remembered that in nearly all practical cases of destruction by electrolysis from stray electric currents, localized pits are produced, which shows that the current generally leaves from localized areas. It is pointed out in the paper that a current density of 0.05 milliampere per square centimeter would cause corrosion to proceed at the rate of one centimeter in seventeen years; this is equivalent to approximately ⅛ in. (0.32 cm.) in five years; current leaving a steel or wrought iron pipe with a ⅛-in. (0.32 cm.) wall, of a density of 0.05 milliamperes per square centimeter, would pit entirely through the metal in five years, provided that the current left the pipe surface uniformly and corroded the pipe uniformly. If, however, the current should leave from 10 per cent of the pipe surface, this same average current density of 0.05 milliamperes per square centimeter would corrode through the metal of the pipe in one half-year, and a current density of only 0.005 milliampere per square centimeter, leaving from 10 per cent of the pipe surface, would pit through the pipe in five years. This very low current density would therefore be dangerous to the pipe.

Regarding the effect of moisture, the authors have found that

as soils are dried the corrosion efficiency is decreased. They suggest that this may be due to the fact that with dry soil the iron is in less uniform contact with the soil, so that the current discharged from localized areas results in higher current density of discharge at these points. This is the logical and probable explanation. I do not believe, however, that this in itself gives much promise of diminished danger to pipes from electrolysis, because while the total amount of corrosion may be less, this may be so concentrated as to be quite as effective in producing pits through the metal of the pipe.

Professor Caldwell has stated that in his opinion it would be undesirable for a municipality to limit the voltage drop in rails by an ordinance, because this would stop them from obtaining damages from electrolysis so long as the terms of the ordinance are complied with. In reply to this statement I would like to say that legal authorities have advised me that the enactment and enforcement of a city ordinance does not take away from a municipality or from the public the common law right to sue for and obtain damages that may be caused by stray electric currents even if the terms of a special ordinance, designed to minimize such dangers, are complied with. The reason is that the common law is superior to a city ordinance.

Burton McCollum: In regard to the point brought up by Mr. Hayden's written communication on the passivity of iron, it would be out of the question here to enter into a discussion of the cause of passivity in iron. It is a matter which has been investigated a great deal, and has led to a great deal of controversy, but I do not agree with Mr. Hayden that passivity is found only when the iron is in an electrolyte in which hydrogen ionization cannot exist—that is, in an alkaline electrolyte.

We are all familiar with the fact that iron is passive in any strong alkaline solution, but we also know that iron can be rendered passive and remain passive in very strong acids. As a matter of fact, there is a great deal of evidence accumulated to show that there are probably a number of different causes of passivity, in addition to those that occur in an alkaline solution.

As to some of the points brought up by Prof. Jackson; he speaks of the effects of moisture on the efficiency of corrosion and on resistance, and seems to be inclined to attribute most of the lack of electrolysis in dry soils to the high resistance. I think, probably, that that is the case, but it might be pointed out that the tendency of the low efficiency of corrosion is to produce the same result as that which would be caused by the reduction of current by the high resistance, so that these causes are superposed, and it is difficult to say how much reduction in corrosion may be due to one and how much due to the other. Probably the resistance is the most important factor.

As regards concrete roadbed, I think it will as a rule give a higher resistance than a dirt roadbed, in which the rails are pretty well buried in the soil. I have made tests of the specific

resistance of water-soaked concrete at the Bureau of Standards, and find that it ranges from 5000 to 8000 ohms per centimeter cube, which is very much higher than the resistance of many earths, but perhaps not much higher than the average of all. The superiority of concrete roadbed is great only where earth resistances are low, but in many cases I think it will greatly reduce leakage currents.

The question was raised as to whether Fararlay's law always holds. In order to answer that it is necessary to say just what we mean by Faraday's law. As Faraday's law was originally stated, it applies to the decomposition of the electrolyte. In modern electrochemical processes, we think of it as applying to all reactions which take place at the electrodes. When we think of it in that sense, Faraday's law always holds. If an iron anode is corroded at 100 per cent efficiency, then one gram equivalent of iron will be corroded by the passage of 96,540 coulombs of electricity, and Faraday's law holds true as applied to corrosion of the anode. If, however, the iron is in a solution which renders it passive, there will be no corrosion of the iron, and in that case the electrolyte breaks up in accordance with Faraday's law, and 96,540 coulombs of electricity will result in the breaking up of one gram equivalent of electrolyte.

If, for instance, an iron anode corrodes at 60 per cent efficiency, then 0.6 of a gram equivalent of iron will be corroded by 96,540 coulombs of electricity, and at the same time 0.4 of a gram equivalent of the electrolyte will be broken up, so that Faraday's law still holds when we consider all of the reactions which take place at the anode.

As to the relative amount of current in pipes in warm and cold weather, it would appear that if the depth of rail is not more than 9 inches and if the earth is frozen to a greater depth than this throughout the entire system, the amount of leakage from the track is bound to be much less than it would be in case there were no frost in the ground, and that would lead me to believe that the current flowing in the pipe under those conditions would be considerably less than if the ground were not frozen.

I want to endorse highly the statement made by Prof. Jackson in regard to the matter of balance between the actual damage and the cost of protection. It is neither necessary nor desirable to eliminate entirely all electrolytic trouble, but the desirable thing is to reduce the loss to such a value that any further reduction of loss would be more expensive than to repair the loss.

Mr. Wreaks brought out the question of coated pipes. We now have in course of preparation a report dealing with the subject of corrosion of coated pipes. I may anticipate the results to the extent of saying that of a very great number of commercial pipe coatings which we have tested we found very few which we considered to be of any value. In fact, they are rather detrimental, because they tend to concentrate the corrosion. There

are some coatings, however, such as extremely heavy layers of pitch, which may give protection for a considerable time, but it is doubtful whether the protection thus secured is worth the cost. Besides, such treatment is merely symptomatic and does not get at the cause of the trouble, and for that reason surface insulation, if used at all, should be supplementary to means applied to the tracks for reducing leakage of stray currents from the rails.

As to enamel coatings for protecting pipes, I think that is a question as to whether they have suitable mechanical properties, and it is also a question of whether they are waterproof. If they are absolutely and permanently waterproof, they will remain insulating and protect the pipes, but if they develop slight flaws and permit the least trace of moisture to soak through and come in contact with the pipes, local corrosion and pitting will occur.

Mr. Bozell brought up the point of placing the pipes on both sides of the street. That is a good thing to do, and it is done a good deal in many places at present. I am confident, however, that that is not sufficient in itself to reduce electrolytic troubles to a satisfactory minimum unless something is done in the way of providing a proper negative return for the current. Besides, we have the problem of protecting pipes already in place as well as those to be laid in future.

Mr. Barker brought up the subject of alternating-current electrolysis. A good deal has already been published on that subject, and among others I may mention a paper by Mr. S. M. Kintner, published several years ago, in the *Electric Journal*, in which he gave the results of some experiments which he carried on with alternating current under practical conditions, and found the corrosion was but a fraction of a per cent of the amount of corrosion caused by direct current. Our own experiments have verified these results, and I do not believe that electrolysis from alternating currents is likely to become a serious problem, except in very special cases.

As to the matter of limitation of the voltages, and such limitation relieving the railway companies of responsibility, as suggested by Mr. Caldwell, I would not approve of any specific limitation of voltage that would relieve the railway companies of responsibility, unless it had been absolutely proved that such limitation was sufficient to relieve electrolysis troubles in a satisfactory manner. Until further data on this point are secured, I do not think it is wise to enter into any agreement that will relieve the railway companies of responsibility for the damage.

The subject of resistance joints in pipes was brought up, but as this subject is being treated at length in a report of the Bureau of Standards, which is now in preparation, I will not attempt to discuss the matter here, other than to say that if properly applied it may have some value as a secondary means of electrolysis mitigation, but the difficulty with it is that if the

resistance joints are not inserted with sufficient frequency there will be such a large drop across the joint as to injure the joint itself, and unless it is accompanied by some primary means of mitigation, in which the potential gradients in the earth are reduced to a low value, it is likely to become very expensive.

I think the subject brought up by Mr. Stott, that of using insulated negative return feeders, is deserving of the most careful consideration. We have given much study to this method of reducing leakage of stray currents into the earth. I am convinced that when properly applied it offers one of the most effective and economical means of attacking the electrolysis problem. This subject is being treated at length in a publication which the Bureau of Standards is preparing to issue shortly, dealing with the subject of Electrolysis Mitigation.

As to the question of current density brought up by Mr. Maxwell, and again by Prof. Ganz, I might point out that the very low current density which he referred to, say 0.005 of a milliampere per square centimeter, if uniformly distributed could not produce any serious damage. Such a current uniformly distributed, even if 100 per cent corrosion efficiency be assumed, would not produce any serious corrosion in less than 100 years. However, the method of measuring the current was such that they measured average current, and undoubtedly the actual density of current discharge was greater than that, and that was responsible for the corrosion which resulted, unless there was a good deal of soil corrosion also. I think, therefore, that the current densities used in these experiments will pretty nearly include the limits within which damage may become serious in practise, though perhaps they should be extended a little further on the lower side, in accordance with the calculation of Prof. Ganz. By current density, we mean not average current density, but the current density at the point where the current is going off the pipes or where pitting takes place.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright, 1913. By A. I. E. E.

THE NATIONAL ASSOCIATION OF CORPORATION SCHOOLS

BY F. C. HENDERSCHOTT

The idea of a national association of corporations maintaining or desiring to establish educational courses for their employees grew out of the experience of the New York Edison Company's commercial school. This company has for some years conducted free technical courses out of working hours at which attendance was optional, but the business-getting end of the industry had received little attention. In organizing a school for its salesmen the company found an enormous task on its hands. Being desirous of having the best salesmen possible, it was willing to spend large sums to perfect educational courses. A thorough canvass of existing practise in training employees for effective service was made and many corporation schools were visited. On the basis of these studies an educational system, involving lectures by experts and examinations based thereon, was inaugurated, and proved successful from the start.

The difficulty experienced by the Edison Company in securing data on corporation schools suggested the possibilities of an association that would act as a clearing house for corporations which, seeing the advantages to be gained by educating their employees, wish to start schools. Such an association should be of great assistance in improving and enlarging courses already started and increasing the efficiency of administration of these courses. A few experts were consulted by the officer of the company having charge of the new school work and a temporary organization was effected. The industries were canvassed to determine how such an association would be received and the response from many was encouraging. On January 24, 1913, a

convention was held at New York University, at which a constitution was adopted, officers were elected and provision made for the appointment of working committees. There were present at this convention representatives of thirty-seven corporations, all keenly interested, all desirous of allying their companies with the new organization. In a report issued by the temporary organization this statement was made:

"The purposes of the association, in brief, are to render new corporation schools successful from the start by warning them against the pitfalls into which others have fallen, and to provide a forum where corporation school officers may interchange experiences and so improve the instruction in their respective schools. The control is to be vested entirely in the member corporations, thus admitting only so much of theory and extraneous activities as the corporations themselves feel will be beneficial and will return dividends on their investment in time and membership fees."

The report suggested the necessity for the appointment of committees on instructors, on allied institutions, and on education. It contained also the following recommendations:

"1. It would seem to be a serious error for the association to attempt to formulate courses.

"2. The association does not propose to institute correspondence courses, since such activity would be far removed from the purposes of the association.

"3. The association recognizes that each corporation has its special requirements. It will be its object to aid the individual corporation in perfecting courses which best fit its needs."

The following articles from the constitution are worthy of quotation, since they show the plan of membership and the emphasis placed on the corporation as the controlling factor.

"ARTICLE III—MEMBERSHIP"

"Section 1. Members shall be divided into three classes: Class A (Company Members), Class B (Members), Class C (Associate Members).

"Section 2. Class A members shall be commercial, industrial, transportation or governmental organizations, whether under corporation, firm or individual ownership, which now are or may be interested in the education of their employees. They shall be entitled, through their properly accredited representatives, to attend all meetings of the Association, to vote and to hold office.

"Section 3. Class B members shall be officers, managers or instructors of schools conducted by corporations who are Class A members. They shall be entitled to hold office and to attend all general meetings of the Association.

"Section 4. Class C members shall be those not eligible for membership in Class A or Class B who are in sympathy with the objects of the Association. They shall be entitled to attend all general meetings of the Association."

"ARTICLE VII—DUES"

"Section 1. The annual dues of Class A members shall be $50.

"Section 2. The annual dues of Class B members shall be $5 and the annual dues of Class C members shall be $10."

The first meeting of the executive committee was held on April 4. From the reports presented it was apparent that the movement is bound to interest a large proportion of the 200 or more corporations now conducting educational work. The reports showed also that data on the educational courses of industrial concerns all over the country are being collected and classified by the educational committee.

Already the movement has corporations representing a capitalization in excess of three billion dollars, and employing over 500,000 employees.

The following is the list of Class A charter members:—American Locomotive Company, New York, N.Y.; Brighton Mills, Passaic, N. J.; Brooklyn Union Gas Company, Brooklyn, N.Y.; Burroughs Adding Machine Company, Detroit, Mich.; Cadillac Motor Car Company, Detroit, Mich.; Carnegie Steel Company, Pittsburgh, Pa.; Commonwealth Edison Company, Chicago, Ill.; Consolidated Gas Company of New York, N. Y.; Curtis Publishing Company, Philadelphia, Pa.; Dodge Manufacturing Company, Mishawaka, Ind.; Henry L. Doherty and Company, New York, N. Y.; R. R. Donnelley and Sons Company, Chicago, Ill.; Thomas A. Edison, Inc., Orange, N. J.; General Electric Company, Schenectady, N. Y.; Haines, Jones and Cadbury Company, Philadelphia, Pa.; Larkin Company, Buffalo, N. Y.; National Cash Register Company, Dayton, O.; New York Edison Company, New York, N. Y.; Norton Company, Worcester, Mass.; Packard Motor Car Company, Detroit, Mich.; Pennsylvania Railroad Company, Altoona, Pa.; Public Service Corporation of New Jersey, Newark, N. J.; M. Rumely Com-

pany, LaPorte, Ind.; Spencer Trask and Company, New York, N. Y.; Spirella Company, Meadville, Pa.; Trow Directory Printing and Bookbinding Company, New York, N. Y.; Travelers Insurance Company, Hartford, Conn.; Western Electric Company, Chicago, Ill.; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; Yale and Towne Manufacturing Company, Stamford, Conn.

On September 16–19 the first national convention of the association will be held in Dayton, Ohio, under the auspices of the National Cash Register Company. Working plans for the coming year will be adopted.

The field of activity opening for this body is unlimited. Corporations are fast being converted to the theory of training their own men. They no longer expect to find satisfactory help ready-made, but are now applying themselves to the task of making men as well as commodities. The universities and colleges, too, are seeing in this new movement a link, long sought, between our institutions of learning and the business world, and are anxious to affiliate and push forward this new educational system.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 24, 1913.

Copyright, 1913. By A. I. E. E.

VOCATIONAL EDUCATION IN PHILADELPHIA AND VICINITY

BY A. J. ROWLAND

Vocational Education is a term which has so wide a scope that in the following brief report certain limitations will be established which will, it is hoped, tend to give a larger value to the statements made in it. The first limitation is to consider only those kinds of vocational education which would be certain to be of direct interest to members of the American Institute of Electrical Engineers. Having some doubt as to how much vocational and professional education overlap, and realizing that the general character and purpose of regular engineering courses, and, for that matter, of manual training and trade school courses, are quite well understood, the writer has decided further to limit the scope of his section of this report to information regarding education offered and made available to men whose employment is in or closely related to engineering industries. He does this with a certain amount of regret, believing there are points of interest and matters worthy of discussion which might be noted in regard to various institutions in the vicinity of Philadelphia which cannot be referred to. Among other things he has in mind the engineering courses at Drexel Institute, which have been operated with increasing success for many years, although nothing has ever been put into print regarding them, except that which appears in the regular printed circular. They are laid along lines somewhat different from those found in university courses on the one hand, and are quite different from courses in trade or industrial schools on the other. Those who operate them believe they fill a distinct place in engineering education and have

a merit that has not been widely recognized mainly because no publicity at all has been sought for them.

Having defined the particular field of this section of the report, most of what is stated hereafter relates to evening class instruction; since the man who is to have technical training in this vicinity must in nearly all cases obtain it "after hours."

General Conditions in Evening Education

In Philadelphia the educational opportunities offered to workers are not copied from plans worked out elsewhere, which are now on trial here. In every case the classes have been formed to meet some definite need which has been felt. Out of this very condition of affairs has arisen a process of development in each institution, all its own, made with little or no regard to what others have done or may have found desirable. At the present time, however, a strong feeling has arisen that considerable improvement could be made by securing a mutual understanding of plans of courses and purposes of the institutions giving them. There is certainly strong indication, also, that employers as well as employees are waking up to the commercial value of technical education. Through better understanding of each other and by hearty co-operation between schools and large employers, there is every reason to believe that the future of vocational education is to be worked out in ways which will be for the good of the city.

Evening Class Problems

Evening class work in Philadelphia presents certain problems which are, no doubt, the same as those encountered everywhere; but a statement of them here will help to make clearer the particular kinds and arrangements of class work mentioned later.

Many men wish to be given instruction at once and only in the particular branch of knowledge in which they feel a need; they are impatient of preparation in mathematics or science or any other subject. Thus a man may never have gone beyond those branches included in primary school education, but he wants instruction in alternating currents and cannot understand why he cannot be immediately taught as much of this subject as anyone else knows. Standard systems of education as used in day schools will not meet the requirements.

Those who seek evening class work are often short-sighted in considering the kind of training which they need. Thus a man employed in the Department of Public Works may seek a course

on "the laws regarding garbage removal," seemingly unconscious that for his real advancement he should have instruction in sanitary engineering. Or another man wants to study "telephones," not realizing that, could he get the opinion of the head of his department, he would find that for real progress in telephone engineering he must have a broad knowledge of physical science and in particular a thorough comprehension of electrical principles and applications.

The same narrow view of what they need makes it difficult to get students to pay attention to a proper use of the English language; to be careful of penmanship and spelling; to be neat in arranging data; or to have any care except to get certain particular knowledge of technical subjects. They are likely to have no thought of developing their mental powers or of widening their outlook either for the practical purpose of increasing their opportunities in life, or of securing education merely for its own sake.

Many a man finds that tuition charges, even though they are very small, along with expenses for books, carfares, and perhaps for clothes, to maintain a creditable appearance before his classmates, make a bar so absolute that evening class work is impossible, no matter how much he would like to take it. This is particularly true of more mature men with family responsibilities, great numbers of whom feel their very great need and yet realize the hopelessness of satisfying it.

Other difficulties might easily be presented: there is the short time available for teaching a given subject; the fact that, coming at the end of the day, men are tired and ready for rest; that often long distances must be traversed to reach desired classes.

Methods Used to Meet the Problems

In connection with the descriptions of classes and courses later, it will be found that various definite methods are used to meet the problems just stated. In some places students are accepted for engineering training, no matter how limited their knowledge. The instruction is then put on a very elementary basis and the student gets what he can. Every technical subject can be explained to some extent without demanding of the student a preliminary knowledge of mathematics or science. Much good work is done this way, especially for those whose interest is slight, or whose mental powers would not respond to any such training as commonly precedes the study of engineering subjects.

Some classes are at the other extreme. Definite entrance requirements are set and the subjects are given on the same basis as regular college instruction.

Most institutions arrange *among their own courses* to so fit things together that the education of a given year may lead on to other things or the work of a single class be widened out into a whole set of subjects, thus providing a way to lead men on without loss of time as their views change and they come to understand the breadth and bearing of the topics they have begun to study.

Difficulties of many other sorts are met by plans which need not be described in detail. A short time to cover a big subject puts both teacher and students on their mettle; no time can be lost; every topic undertaken must have a definite aim. Unless each evening the student feels that the loss due to staying away is so great that he cannot afford it, something is wrong with the subject or the instructor. One of the advantages of evening class education is that the class has a definite goal and must make definite progress toward it every time it meets.

The difficulty of the classes being *evening* classes is much overestimated. Everyone who has passed the regular "going to school" period in his life does much of his studying evenings; they must be used if one hopes to keep up to the times. The stimulus of a class at work; of an enthusiastic teacher; the possibility of learning by the mistakes of others as well as by one's own; the possibility of direct explanation of difficult points; the embarrassment of being called on for something one has not looked up—all lead to the certainty that far more can be gained by class work than by sitting quietly by the library lamp at home with the best book on the subject in hand. Sleepy and dull students in an evening class usually reveal a dull, unresourceful, or incompetent teacher.

The financial problem of the evening student is one of the hardest to solve. Experience shows that free classes are not successful. Few people value that which costs them nothing. Most institutions conducting evening classes do not expect the receipts from tuition to come anywhere near to paying the cost of instruction. The tuition fee is commonly so low that it is frequently a small part of the total expense. The writer knows of cases in which the railroad fares, alone, of students attending his classes were five or six times the cost of tuition. By keeping the expense at the lowest possible figure, it is certain that many ought to be reached

who simply cannot afford to pay the bills. As far as the writer knows, there has been no firm in Philadelphia as yet that has made arrangements to offer to help its employees in this matter. This is one point where it would be pleasant to see the practise in some other cities adopted.

Possibilities in Evening Education

The possibilities in evening education are hardly realized by most people. It is only those who know how evening students work, and the way they push on, who can appreciate how much they can absorb in a limited time if the work is carefully laid out. It sometimes seems as though the very fact that their attention in school work is focussed wholly on one or two subjects enables them to grasp new things and understand difficult matters in an unusual way. In a majority of cases students who seek vocational training in evening classes are already employed in work of a definite character in which they see prospects of advancement. They know what kind of knowledge they want and what they are going to do with what they get. They see at once the practical bearing of theoretical principles and have a point of view quite different from that of most students—even college men.

It is a pity that the miscellaneous character of evening courses which are offered, and the diversity of entrance requirements, lead to misunderstanding in many cases as to what those who finish them really know. While very elementary work is done in subjects commonly considered the heavier and more theoretical in engineering work, there are, at the other extreme, courses for which exacting entrance requirements are set, in which, in character and scope, the training is equal to that given seniors in college.

Exclude shop courses and the like for rather obvious reasons, and the writer believes that if a *comprehensive* plan of dealing with this matter of kind of courses and entrance requirements were possible, men could be properly classed by considering their previous knowledge and started on courses of training which could be indefinitely continued; while the student would be sure of direct value from what he had taken, no matter at what point he chose to interrupt his course. At present a man starting upon a vocational course is likely a little later on to find that he has reached a point in education from which he can make no direct advancement. If he enters a trade course, some bar in

mathematics or science will prevent his going on with advanced work. The knowledge he already has in the line which interests him must be dropped and a new start be made. A man who has done well in a trade course in plumbing cannot enter a class in sanitary engineering even though he knows much more about practical problems in the subject than many men who have a different preparation. The pity of it is that there are always a few men who take courses of a simple kind, the best in their classes, who should be encouraged to go further. Such conditions are especially bad when a change from one institution to another must be made.

If such a comprehensive plan were possible, the applicants would be divided into four grades:

1. Men who have completed technical high school courses; who are therefore ready by educational preparation and by mental ability to enter immediately college grade work, which would be provided for them.

2. Younger men and boys who have completed or nearly completed grammar school training. They may be given work of high school character selected so that they shall receive, in as brief time as possible, training in subjects making them able to enter classes along with those received directly into grade 1.

3. Older men who have been long away from school work and who find mathematical operations and technical reasoning hard. They should immediately be given training in principles and practise along lines in which they need instruction, but with such arrangements that along with this they may gain that knowledge of mathematics and science which will eventually, if they choose to continue their study work long enough, lead as far as the courses arranged for men in grade 1.

Into such an arrangement men may fit who occupy positions of responsibility, or who for special reasons would feel uncomfortable in classes with boys fresh from school, and do excellent work there. The writer has conducted classes of this character in which men over sixty years of age were scholars.

This grade also provides a definite place for men who hold executive positions and want a sort of "business-engineering" training of somewhat indefinite scope.

4. Similar to grade 3 but arranged for boys and young men who must secure a certain amount of technical training at once; or who are not sure until they try it whether their tastes run to a life work along technical lines. Men and boys who seek instruction in trade courses belong in this grade.

A man who followed along any of these lines as far as he could go should have a training equivalent to that of a college or university. His course, however, might be many years in length.

The Part the School Should Take

In any educational scheme the scope of the school work has to be determined and limits set for it. This is as true for vocational education as for any other sort. The writer believes that the tendency of the day in many lines of vocational education is to do too much in the school; while in others the part which schools should take is scarcely recognized.

In vocational work connected with the trades the first difficulty is common. Very many schools give trade instruction in the machinist and pattern-making trades. Starting with these two, it is very easy to expand to include a dozen others, and then the question arises as to why only these particular ones should be taught. Why should not instruction be provided for every trade under the sun? Such elaboration involves requirements in the way of space and equipment which are appalling to contemplate. An army of specialists to teach all these things would have to be found. Now by reviewing the trades and the kind of instruction required in each, it is possible to find certain principles and practise common to large groups. It would be easy to pick a group in which an ability to read drawings is required, fundamentals regarding force, work, power, pressure, etc., apply in all; a knowledge of belting, shafting, and transmission machinery is essential; certain principles regarding the kinds of tools used and how they are best used are needed in every trade. The school can easily give instruction in such lines and its equipment would naturally be planned for it. The direct use of particular machinery, on the other hand, and the detailed application of principles to a particular trade, ought to be gained under strictly commercial conditions in connection with the production of a definite output. This usually involves special methods and machinery distinctive to each plant and factory. Instruction to this end should be given in the factory itself and be specialized to the extreme.

The same thing holds outside of trade instruction. In the electrical industries, if knowledge outside the routine of daily work is desirable at all, much of it applies to *every* line of work. The general principles of direct and alternating current flow come into everything electrical. A knowledge of resistance and im-

pedance once gained, the employee of a telephone company makes the application as readily as the man operating machinery in an a-c. generating station. The generation of e.m.f. by cutting flux and the arrangement of armature windings for dynamos and motors have enormously wide application. The principles are as important to the switchboard man in a central station as to the armature winder in a repair shop. Mechanical thrust on conductors carrying current in magnetic fields of force, and speed and torque relations for motors, have an interest to the instrument maker; while their application is readily made for himself by the man concerned with interurban car work.

The equipment required in order to show a student any of these things is so different from that found in commercial uses, while electrical apparatus once installed affords so little opportunity for intelligent examination of its properties, that no corporation is able to give instruction in such principles to its employees unless the equipment of the school laboratory is duplicated; and if it is, the experienced teacher is lacking. Few people realize how scant are the opportunities to learn in connection with practical work. Regular class work accompanied by individual laboratory experience is the only way. On the other hand, the school can never teach satisfactorily a great variety of subjects important to be known by employees if they are to be of real use to their employers. Such topics are: the arrangement of a distribution system, and why; the use of certain kinds of equipment in connection with certain kinds of installation; kind of insulation used, and why; preferred practise in operating or in dealing with troubles, etc.

Hence, in all sorts of vocational work the school and the corporation each has its own part to play; each a special kind of instruction to give.

Examples of Courses

1. *Drexel Institute* has conducted evening classes for twenty years. The principles upon which they are founded are, that the same opportunities shall be offered as to day students by the same trained faculty used to the work and working together. Every member of the faculty personally teaches evening classes; all the facilities of shops and laboratories are put at the disposal of evening students.

When the work was started, a list of courses like those for day students was made up and offered in evening classes. Instructors met those who came; found what they were seeking and planned

definite classes and inter-relations of classes to meet the requirements. This process has been continued to the present time. One of the remarkable things connected with it is the constant demand for work of still higher and more exacting character. The classes now cover nearly as wide a range as for day students, although they are planned expressly for the men who come to them and are largely elective. The Department of Science and Technology includes mathematics, chemistry, physics, electrical engineering, mechanical engineering, and civil engineering. The classes at present offered by this department include forty different ones, twenty-three being engineering subjects. Definite provision is made to receive students at either the end of grammar school education or the end of a high school course. All students must meet fixed entrance requirements; usually by examination. Any subject may be taken separately if its entrance requirements can be met. Five years ago, on account of a certain demand, elective groupings of higher grade science and engineering subjects were offered, and now a considerable majority of the students are enrolled this way for rather long courses. The normal rate of attendance is three evenings per week for the six months October to March, inclusive. Enough home work accompanies any course to occupy most of the other evenings of the week. The fees are very small. A young man who enters at the point where grammar school closes, must attend for three winters in order to reach a point where he can meet the entrance requirements to subjects arranged for those who have completed a high school course before beginning their evening work. Two more years of training lead to a certificate granted for a "major" in some division of work in the department, and a "minor" in another. Most of the students are quite mature. During the past session 775 men were enrolled; 489 of them for comprehensive courses. A considerable number of students come to the evening classes from points outside the city; some from as far as thirty or forty miles away.

Along with the regular engineering classes certain ones are included of rather elementary character. Applied electricity, as an example of one of them, is given only to mature men, and deals with the topics of dynamos, motors, lights, and wiring. To enter it, a knowledge of simple arithmetic, including mixed numbers, decimals, percentage, and proportion, is required.

In addition to the courses mentioned, Drexel Institute offers shop training to a limited number of men in machine and wood

shop; to a considerable number in drawing courses following old-fashioned lines; to a group in architecture and building construction. The total number of men students in evening classes, 1912-13, is nearly 1100.

2. *The Franklin Institute* has offered evening class work longer than any other school in the vicinity. Courses in chemistry, natural philosophy, mechanics, architecture, and mechanical drawing were established in the spring of 1824. The mechanical drawing classes have been given continuously since.

A dozen years ago a demand arising through drawing work was met by establishing classes in elementary mathematics. A local demand from men employed in the shipyards of the vicinity for training in their line of work came at about the same time. Out of these grew other demands, extending the scope and character of the instruction offered. The work is now conducted in four departments: drawing, mathematics, mechanics, naval architecture. The mechanical drawing is comprehensive; the mathematics includes the high school branches; mechanics includes strength of materials, machine, structural design, and steam engine; naval architecture includes three classes succeeding one another. This last subject illustrates very well the way in which classes have been formed to meet local needs. Philadelphia has two large shipbuilding companies and many smaller ones in or near it. A very close relation exists between these companies and the course in naval architecture.

During the session just completed 305 students were in attendance. Entrance to classes is by certification from Philadelphia schools; by transfer of credits from schools in other cities; by examination. The school year is made up of two terms of fourteen weeks each, the classes being in session from 7:15 to 9:15. Most classes meet two evenings per week. The fees are nominal.

Most people know the Franklin Institute and understand how, through its many activities, the city is under obligation to it. Through lectures, researches, its library, and its *Journal* a very wide educational work is carried on.

3. *The Y. M. C. A.* in Philadelphia is a bureau of information at which very many young men inquire when seeking advice regarding self-improvement. In the past few years it has been decided to establish classes in technical lines. Among other special kinds of work for which a demand has been made is instruction in estimating. During the past session, in the School of Mechanic Arts, classes have been conducted in mechanical

drawing, including shop mathematics; in physics; in applied electricity; and in chemistry (an elaborate course covering the range of college work). At the request of the Department of Public Works of the city government, classes in engineering for power plant operators have been organized with moderate success. A very successful class in practical chemistry for laundrymen affords an example of a real cooperative class arranged to meet a local need. The School of Building Construction includes subjects in "practical work only, taught by practical men." They are architectural drawing, mathematics, building construction, estimating from building plans or specifications; heating and ventilating, including estimates; and electrical construction, including estimates on electrical equipment.

In some of the classes the aid of experienced teachers from the Williamson Free Trades School has been secured.

The laboratory equipment for the work is being gradually increased. Much larger facilities are expected in connection with new building construction about to begin.

The sessions run from the end of September to the end of May, the fees corresponding to those of other local schools.

4. *Temple University*, in its College of Arts and Sciences, offers evening, afternoon, and Saturday classes. One of the original purposes in the founding of this university was the arrangement of a college course for students who could not attend regular day sessions. The work is of the same grade and scope as that undertaken in the day classes and students who have fulfilled the entrance requirements are given credit toward the bachelor's degree for such work. Special students, properly qualified, may be admitted to any of the classes. In forming courses, the subjects are not arranged in the usual plan for four college years, but according to subject matter; the student taking a larger or smaller number of classes according to his circumstances. In technical work a civil engineering department is established, the classes including those usual in a standard college course. The classes are put into five groups: I. Preparatory to engineering groups (mathematics, drawing, chemistry). II. Surveying (including descriptive geometry, railroads, calculus). III. Structural engineering (strength of materials, roofs and bridges, bridge and truss design). IV. Hydraulics (including steam engine and applied electricity). V. Other subjects required to gain the degree of B.S. At the present time no students have advanced beyond the work which naturally falls into the sophomore year of a college course.

5. *Spring Garden Institute* conducts a three-year evening course in electricity. This was originated by the late C. Walton Swoope, whose text book, "Lessons in Practical Electricity," is widely known. The course has the distinct merit of originality and individuality. Students are accepted for the first year's work without any requirement except their wish to follow the course. The first year's instruction is obviously the most difficult for the teacher, and is given partly by lecture and partly by an ingenious system of class laboratory work. Mathematics and science required to understand the electrical work are given as part of the instruction. The first year's class is limited to 150 students; 100 is the preferred number. Students attend two evenings a week. In later years of the course individual laboratory work takes most of the time. The laboratories have a good equipment and the work is well planned. The course includes little or nothing which would be found in an electrical trade course. There seems to be no demand for that kind of work in Philadelphia; the school work is limited to explaining "how" and "why" and verifying the facts by experimental measurements.

The Spring Garden Institute also conducts a course in metal shop work, particularly for machinists, which is attended by a moderate number of students.

6. *The Philadelphia Textile School* of the School of Industrial Art conducts evening classes in a large number of subjects relating to the textile industries. Philadelphia contains between seven and eight hundred spinning, weaving, and knitting establishments, and more than one hundred dyeing and finishing works. The presence of these, along with all the allied industries, including the makers of machinery for these manufacturing enterprises, explains the need of these classes. The evening classes cover in a general way what is given in the day classes. Weave formation, warp formation and weaving; fabric analysis; study of power loom; cotton, woolen, worsted yarn manufacture; chemistry and dyeing; jacquard design, etc., are included, and groupings of subjects are made to meet the particular requirements of each individual case. This is true vocational work given to men who want far higher and better knowledge than simply how to operate the machinery of the industry, a knowledge which cannot possibly be obtained as part of their daily occupation. The laboratories contain a large amount of machinery and appliances which are used in connection with the evening work so far as time available and the nature of their products will permit. The same faculty

which conducts the day classes handles the evening work in the same subjects. Attendance is three evenings per week for the term of six months, the fee for any of the regular courses being $15.

In the art department of the same school, classes are offered in industrial drawing, constructive design, and pottery.

7. *The Philadelphia Trades School* is the first in the United States to be conducted as part of the public school system. It was opened in October, 1906. At the present writing an annex is operated in connection with it (both in the central part of the city), and another school (No. 2), under separate management, is conducted in a different district.

In the evening classes of school No. 1 over a thousand men are receiving vocational training in bricklaying, carpentry, pattern making, electrical construction, architectural and mechanical drafting, house and sign painting, plumbing, printing, sheet metal working. The largest classes are those in electrical construction (216), in plumbing (262), in sheet metal work (142). The two last named form true vocational schools of the cooperative type, for students are not accepted unless they are working at the trades in which they seek instruction.

The whole sheet metal working industry not only endorses the course in this subject and encourages the attendance of workers, but has made attendance at the school part of the apprentice agreement. The students come from fifty-six shops in the city. The course is four years in length and requires attendance three evenings per week for a six months' session in each year. Training in the trade work takes most of the time, but work in mensuration, geometry, simple physics, and mechanical drawing is included.

The fact that the cooperation of the Master Plumbers' Association in the plumbing course is as thorough and satisfactory as that of the Sheet Metal Workers shows their estimate of it. The work follows similar lines to those of the class described in the preceding paragraph. There is no regular apprenticeship among Philadelphia plumbers, but there is a state law demanding examination to secure master's licenses, and graduates who are twenty-one years old (the minimum age) easily meet the requirements.

In most trade courses the instruction is rather closely limited to developing intelligent skill in manipulation. Mathematics or drawing is made to fit closely to the trade requirements. The

class in electrical construction follows somewhat different lines. There is a mathematics requirement and the course runs for six winters to graduation. Mathematics instruction is carried through trigonometry, and the electrical instruction includes considerable theory along with the trade work.

It is very probable that in the immediate future close relation may be established with trade organizations in other trades precisely like that now holding for plumbing and sheet metal working. Continuation school work is also likely to be established in the near future.

8. *The Pennsylvania Railroad.* Within a few months past a definite course of instruction in electrical engineering and associated subjects has been offered the employees of the Pennsylvania Railroad under the direction of Mr. J. C. Johnson, superintendent of telegraphs. This is a correspondence course devised especially to meet the requirements of railroad men. That it has been well received by those for whom it has been prepared is plain when it is stated that at the present time about eight thousand men have enrolled as students, with the prospects good for an enrolment of more than ten thousand soon. This has happened without any attempt to urge the course on the men; they have rather clamored for the opportunity to take it. The establishment of the course has, however, nothing to do with the "electrification" of the system in and around Philadelphia. The course was launched and the students enrolled before this was decided on. The instruction is not especially directed to topics connected with traction problems.

This educational course is not a thing begun in haste. It is simply the last step which has been taken as a natural development of efforts made to help those who have never had a chance to secure technical education. Mr. Johnson for twenty years past has been doing educational work with and for railroad employees with whom he has been associated.

When this correspondence course was considered and about to be started, it developed that men in all departments of the company wanted to secure its advantages. As Mr. Johnson himself says, "Where can the line be drawn? Every railroad employee from the president down, touches electrical applications of some kind in his daily routine. It may be in connection with the telephone or the telegraph, or call systems, or in connection with lighting or motive power. Everyone in all the departments wants to know something about electricity."

So far, four well-illustrated pamphlets have been issued, as follows: "General Information," "Mathematics—Elementary Arithmetic," "Elementary Electricity—Primary Batteries," "Elementary Electricity—Direct Current."

The complete course is to cover a wide range of subjects, including drawing, mathematics, telegraphy, telephony, signaling, lighting, electric traction, power plant apparatus, and line construction. In electricity alternating-current as well as direct-current principles and applications are given. The instruction can be secured only by employees of the railroad. The papers and pamphlets are furnished them free of charge with the understanding that they may be kept for future reference. So much work has already arisen in connection with answers to the questions which form the lessons, and from the "question box" which has been established, that branch offices have been opened in Buffalo, Pittsburgh, Altoona, and two in New York.

It is certain that even though only a small proportion of the men who enroll go on to finish the course, all will at least have gained some knowledge. It is with this feeling that the course has been launched; a desire to do as much as possible for employees who are hungry for knowledge, many of whom by environment, location, or character of daily employment have never had the opportunity to learn.

The School of Telegraphy of the Pennsylvania Railroad is another important educational work. This school is located at Bedford, Pa., a location selected so that the expense of a course can be kept to a moderate figure. It was started by Mr. Johnson in 1907 and is of course under the control of his department. Healthy young men between seventeen and twenty-five years of age having a fair common school education are eligible to its classes. Students may enter at any time and are graduated in six or eight months. A small tuition fee is charged, but after graduation this is returned. At graduation all are given positions with the railroad and on proving their worth, are in line for promotion. The school has an equipment for teaching not only telegraph sending and receiving, but also the use of the telephone in connection with railroad work. A complete telephone train dispatching system is in operation, consisting of a dispatcher's outfit and way-stations with selectors. A miniature railway is installed with block signals, etc., on which trains are run, the stations being equipped with main line instruments,

switchboards, and signals, each in charge of a student operator. Block and train orders, messages, and reports are transmitted as they would be in regular service.

The instruction further includes the duties of a station agent; account keeping on the company's regular forms; and the book of rules for the government of the transportation department. At present there are about twenty-five young men in the school.

In connection with the Pennsylvania Railroad Y. M. C. A. work in Philadelphia, there was established two years ago a course of lecture instruction on railway electricity for motive power purposes. During the first year this was of general character, the lecturers using lantern slides, models, etc., to explain in general terms the systems and the apparatus in use for such work. The second year the course has been more definite, more direct instruction methods being used. The class has been in charge of Mr. Eugene P. Chase, electrical instructor of the Pennsylvania Railroad at the New York terminal. With the aid of full-size interurban car equipment, the work has been made very practical. The writer has been particularly interested in this class, as the result of his having the honor and pleasure of giving the instruction at the beginning of the course on the general fundamental principles which apply. It has been remarkable to observe how a class of sixty men, many of them in mature life, most of them holding responsible positions, such as road foreman of engines and the like, have held together through bad and cold weather with a constant, lively, maintained interest. The course closes in April. Another class is formed immediately.

In connection with machine shop apprenticeships at the West Philadelphia shops of the railroad, there are regular classes operated on the "continuation" plan, attendance being compulsory and on the company's time. The instruction is handled from Altoona, and was outlined in the 1912 report of the Educational Committee of the Institute on "Industrial Education."

9. *The Bell Telephone Company's Plant Schools in Philadelphia.* Eight years ago an installer's school, primarily for the systematic instruction of the employees of the plant department of the Bell Telephone Company, was established. An enormous increase in plant extensions to meet the demand for telephone service had to be made and the required number of trained maintenance employees and private branch exchange installers could

not be secured. During 1906 the company enlarged and perfected the school work, carrying on a Central Office School and separately a Private Branch Exchange School and a Substation School including line and cable work. These schools have been abandoned. They were required and considered a necessary part of conducting the telephone company's business while thirty per cent, or less, of the men of the plant department were unskilled workers. Today probably 90 per cent of the employees are trained men, and in connection with their every-day work they, or some of them, assume the responsibility for the proper instruction and training of apprentices or helpers.

While the schools were operated, they were managed by men whose whole time was given to teaching, and were so conducted that regular instruction in electrical theory, in so far as it would apply to the practise of the company in telephone work, was given in a systematic school way. The equipment included circuit charts and standard apparatus. The methods of practical instruction were carefully worked out to fit the requirements of the case, and as many as forty students were cared for at one time, an average of 300 students passing through the schools per year. Not only new employees, but older ones, were brought into the schools, the number attending at any time depending on the amount of work then in progress or in prospect. In the case of *new* employees about seventy-eight per cent passed the instruction work with an average considered sufficient for continued employment. The Substation School was of lower grade than that dealing with central office equipment and apparatus. Admission to the Central Office School was granted ordinarily only to those who had had the other training and a considerable amount of practical experience. The period of instruction in each school was about six weeks, during which period each scholar was paid his regular rate of wages. Some graduates of the school deserted the company, but the loss due to this cause was not considered a serious factor in determining the commercial value of the schools.

10. *Firms and Corporations* conducting school work for their employees in Philadelphia or its vicinity are very few. The large department stores have such classes, but those which are vocational are not technical. The only firm doing anything directly is Fels and Company, as noted in the next paragraph. The New York Shipbuilding Company (Camden, N. J.) has an apprenticeship system including four years of 2500 hours each. A

definite time allowance is made for time spent in the classes of a selected list of schools, based on the actual attendance of each man, governed by his averages and the benefit he has derived from his studies. No arrangement is made for instruction in the shipyard because of the proximity of schools in Philadelphia and Camden. William Cramp and Son's Ship and Engine Building Company in its electrical department has an arrangement somewhat different from the usual apprenticeship system, which has been in operation for six years. Each apprentice spends three months' time in a particular department of work and passes from it to another only after he has been examined and shows that he knows what he has been doing. No instruction of a class room kind is given. What he learns he picks up in connection with his every-day duties.

A number of boys and young men are employed in the soap-making works of Fels and Company whose positions, in the nature of the case, lead nowhere. Realizing this, and believing that such young men should have definite opportunity for advancement of some kind offered them, the firm gives each one the opportunity to spend one week in four in the machine shop, where as definite a course as possible is laid out for them. At the end of three years these men are assisted to positions in other firms where they advance in the machinist and kindred trades. In addition, free evening drawing classes are open to the same men during a considerable part of the year, the firm supplying the necessary equipment.

11. *Education for City Employees.* Those at the head of the present city government realize that in city employ, as in any private undertaking, the matter of the educational advancement of the individual employee is of prime importance. The Mayor, therefore, a few months ago secured the appointment, through the Superintendent of Public Schools, of an advisory committee from the faculties of the various high schools, who should on request direct men and women engaged in the city's service how to improve themselves, so as to be in line for promotion. This committee met semi-monthly from November to April inclusive, during which time 180 persons from the Departments of Public Works and Public Safety, the ones most interested, called for counsel. They have been given advice as to existing educational opportunities in schools, have had courses of reading suggested, etc. Some thirty-five of the number wanted to secure engineering training of collegiate character.

At the present time in Philadelphia, except for the Trades Schools already mentioned, there is no vocational training available in the public school system for those who are employed. The only agency prepared to deal in a broad and disinterested way with the subject of vocational education and vocational guidance for both those now employed and the young people still at school, is the Public Education Association (composed of a volunteer membership of a thousand citizens). Through its secretary a solution to the many problems is being sought.

12. *Electrical Department of the Underwriter's Association.* A novel movement with an educational motive was started a few months ago when the chief of the department, Mr. Devereux, invited inspectors of the city, inspectors and managers of the Philadelphia Electric Company, and electrical contractors and their superintendents to the semi-monthly meetings of the inspectors of the Philadelphia Fire Underwriters' Association. Starting with thirty, the number attending has increased to one hundred and fifty. The character of the meeting has become one of free discussion and question asking—very much more educational than most such gatherings. The topics discussed are the National Electrical Code, city regulations, and any puzzling subject which may be brought up through a question box which is opened at each meeting.

13. *The School of Industrial Arts*, Trenton, N. J., is the only school within a range of many miles from Philadelphia providing vocational education for those who are employed. It was established 1898 in pursuance of "An Act Providing for the Establishment and Support of Schools for Industrial Education" approved by the Senate and General Assembly of the State of New Jersey, March 24, 1881. The act provides for "the establishment and support of schools for the training and education of pupils in industrial pursuits (including agricultural) so as to enable them to perfect themselves in the several branches of industry which require technical instruction."

The school is supported by the state of New Jersey and the city of Trenton. Courses in machine, building, electrical and pottery trades are offered. The school has had a fine building erected for and presented to it in 1910, an equipment which is adequate to the work undertaken, and a director endeavoring to make the school fit the industrial conditions. Trenton has large pottery industries, rubber works, wire mills, and a railway repair shop. There are over 600 students in the evening classes.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 24, 1913.

Copyright, 1913. By A. I. E. E.

THE PENNSYLVANIA RAILROAD COMPANY APPRENTICE SCHOOLS

BY JOHN PRICE JACKSON AND J. W. L. HALE

In dealing with the subject of the Pennsylvania Railroad Apprentice Schools, certain explanations are necessary, inasmuch as this system of schools has been developed on a plan somewhat different from those maintained by most other large industrial or transportation corporations.

The cardinal purpose of the corporation named—in harmony with that of others—is to prepare young men for efficient service in the mechanic arts related to its particular business. In this case many of the young men will later become locomotive firemen and engineers, skilled mechanics in engine and car shops, operators in power plants, draftsmen, etc. It was, therefore, very carefully determined at the outset that the apprentice school work should be so given as to develop in the young men a proper ambition to become skilled in work of this character and at the same time to avoid developing in them the discontent and unhappiness which comes to those whose aspirations are beyond their capability or circumstances—as would be the case if they were led by their instructors to believe that they should attain positions in which manual skill and labor is not required. Incidentally, however, it was carefully specified that such records should be kept as would enable the company to lay hold of the small percentage of the total number of apprentices who, by reason of exceptional brain power and ability, should be advanced beyond the ranks of skilled workmen to the ranks of those who direct the labor of others.

Though the purposes and aims stated in the last paragraph are carefully observed, nevertheless the directors of these schools

frankly admit that they are more largely schools of the mind than is usually admitted in the case of similar institutions. However, the work of the schools is carefully related to the work in the shops, and there is very *close affiliation between superintendents and foremen in the shops and the instructors in the schools.* Foremen are the shop instructors of the young men. The reason for this unusual arrangement is the belief of those in charge that a foreman who has the intelligence and capability to do his work well, and who has a sufficiently broadminded interest in the progress of his organization, will likewise have the ability and desire to instruct the apprentices efficiently. It is indeed believed, and experience has shown the truthfulness of the belief, that good foremen are unusually efficient in following up and teaching these young men. By having the whole responsibility on his own shoulders, so far as the shop instruction goes, the shop foreman must, of necessity, take a personal interest in the advancement of the apprentice. Failure on the part of the latter is directly debited to the former by the general officials. The fact that a single man in a department has this responsibility and that it is, therefore, not divided between foreman and shop instructor, with the consequent unsatisfactory results of divided authority, is an argument well worth consideration.

The apprentices are moved from department to department of the shops very much as in other establishments, and have carefully arranged shop apprenticeship courses. A complete system of records prevents young men from being held up unduly on any particular branch of the work, and keeps the company officials and school instructors fully informed concerning the comportment of the young men while in the shops. In the following pages the schools proper are described. It must not, for that reason, be thought that there is any neglect of the training of the apprentices while in the shops. This feature has been worked out in great detail.

The Pennsylvania Railroad Schools now consist of the parent institution established in Altoona, Pa., where the number of apprentices attending is in the neighborhood of 260, and the more recently established branches located in Philadelphia, Pa., Wilmington, Del., and Harrisburg, Pa., in which the enrolment ranges approximately from twenty to thirty-five and forty. The exact number of students enrolled is not here given, since it varies somewhat from month to month. In establishing the schools, the railroad company officials were anxious to make use

of well-established pedagogical methods and at the same time, maintain a very practical course of applied education. The company, therefore, called upon the School of Engineering of the Pennsylvania State College to formulate the pedagogical methods to be pursued and to take general supervision of the schools. As a result, the system has been worked out and is carried on as a co-operative movement between the college named and the railroad officials. An instructor in charge of the entire work is located in Altoona; he is assisted by four other instructors and sufficient clerical service. One instructor only, at the present time, is required to carry on the schools in Philadelphia, Wilmington, and Harrisburg, the remainder of the force being located in Altoona.

In the following brief outline of the work done by the schools and the methods adopted, ordinary names of subjects as used in schools and colleges are given. This is done because, though, these subjects are all prepared for a special purpose and are correlated closely with the work the young men are doing in the shops, they may, nevertheless, with entire propriety, be given their proper names. In some cases special terms, such as "shop mathematics," etc., are used in describing the work of schools of this class. As a matter of fact, the nomenclature in use in our ordinary schools is entirely sufficient for the purpose of denominating these subjects, if it be kept in mind that they are different only in regard to the illustrations, arrangement, etc., of the old, well-established principles.

Monthly, semi-annual, and annual reports of the work of the schools and of the individual apprentices are made out by the head instructor and include attendance, grades for each subject studied, average grades, and comments upon characteristics and capacity. These reports are voluminous and are of such a character as to form a fairly complete record of the aptitude and ability of each man. The records thus obtained, when taken into consideration with the parallel system of reports from the shop foremen, form a most valuable body of data from which selections for the various services of the corporation may be made, and also give the instructors an accurate basis upon which to sift out undesirable material and make proper promotions in the schools. It may be interesting to observe here that a small percentage of the young men show extraordinary ability, and that the company officials have been materially aided by the schools in drawing into their official ranks the very cream of the

entire body of apprentices. Without these detailed and well-established records, many of these men would never have reached the positions of maximum value to the company, with a resultant great loss, not only to the men themselves, but to the corporation. One of the members of the company has made the statement that this possibility, made available through the schools, of picking out accurately the unusual material from the mass, is in itself of sufficient value to warrant the entire expense involved in maintaining the schools.

The work as outlined covers three years of forty-two weeks each. The apprenticeship course itself is of four years' duration. During the last year the apprentice does not attend the school unless detailed thereto, but is assigned special work by the company to give him particularized training for the duty which he is later to perform as a skilled workman. Each apprentice receives four hours of instruction per week in periods of two hours each. These two-hour periods are separated by as many days as the schedule will permit, in order that the lessons assigned may more readily be given as much evening consideration and study as is possible and desirable. The recitation work calls for about an hour of daily study, which must be done during the evening by the apprentice.

In dividing the body of the apprentices into sections, an endeavor has been made to give an individual instructor from fifteen to twenty men in a class. Much flexibility with regard to the classes is maintained; thus, if it is found that a section can be made up which will travel much more rapidly than the average, such a step is taken, or *vice versa*, if a group of the less bright men can with advantage be segregated and given the work in more detail, that arrangement is made. It will be appreciated that this kind of instruction requires more labor on the part of instructors than if an entire class covers exactly the same work, but by using these methods it is possible more nearly to give each individual the training which is best for him, and thus more effectively to prepare him for the service of the company. The necessity of careful class selections is marked in the case of these schools, as the apprentices are drawn from all classes and enter with schooling which ranges from the common school grades to those of a college. Using the ordinary names, adopted among teachers, the curriculum in the school might be said to include a rudimental study of English, mathematics, physics, mechanics, mechanism, strength of materials, chemistry, mechanical drawing, machine

design, steam practise, and shop management. This sounds like a formidable list of studies extracted from some catalogue of a technical college, but as a matter of fact it represents, in reality, a very elementary but thorough system of study dealing with simple phenomena of nature, methods of computation, and the English language, closely allied and correlated with the daily labor of the apprentice pursuing the studies. Indeed, the school authorities want it clearly understood that this school is of a most practical type for improving the quality of skilled mechanics, and not for making half-prepared engineers. Moreover, they wish it to be known that the life of the school has been sufficient to determine the fact that it is accomplishing this function well.

The work in English covers spelling, the meaning of words, parts of speech, formation and construction of sentences, and composition writing, including accurate methods of writing business letters, making out order blanks, time reports, etc. The young man when he is through with this course not only has gained some practical ability to use understandable English, but also to comprehend better such reports and instructions as may be given to him either by word of mouth or in writing.

The work in mathematics begins with very simple shop problems in arithmetic, including the elementary processes of addition, subtraction, multiplication and division, fractions, decimals, etc. Gradually this work is advanced to bring in applications involving some of the most useful elementary principles of algebra, geometry, and trigonometry.

The course in physics includes both class work and laboratory work in elementary principles of heat, electricity, and mechanics, and a short study of light and sound. Practical illustrations very closely allied to the shop work are used exclusively, and the course is given specifically for the purpose of enabling the apprentice to have a keener conception of the processes that take place under his hands while at work. Numerous problems of this character relating to the field of mechanics will immediately arise in the minds of those reading this who are connected with the industries.

The mechanism parallels the work in mechanics and is an applied study dealing with motion, velocity and acceleration, power work, etc., as shown by study of shop machines.

The study of strength of materials deals with the manufacture and properties of materials used in machine construction. Along with this are carried out tests upon various materials in order to give the apprentice a vivid conception of the strength and other characteristics of materials with which he deals in his work.

The chemistry taught includes some of the more fundamental facts which every man connected with industry should know about the chemical reactions and constitutions of materials. Special stress is laid upon the characteristics of water and fuels and the combustion of the latter. Inasmuch as a large number of the apprentices become locomotive men, the importance of combustion as a study directly pointing to the proper use of the boiler firebox is evident.

The course in steam practise deals with such problems as should be understood by locomotive engineers or firemen. In this, as in those subjects heretofore named, the work is very practical, but it is to be clearly understood that much care is at all times exercised to emphasize the underlying physical principles upon which practise is based and to bring the apprentice as far as possible into touch with the phenomena involved, through the medium of his senses.

In mechanical drawing, the student becomes familiar with the standard methods of drawing, dimensioning, and lettering. Models built in the shops are used for sketches from which mechanical drawings are made. These courses are sufficiently extended not only to give some skill to the apprentice in presenting his ideas accurately on paper, but also to enable him to read shop drawings accurately and readily.

The machine design course is a continuation of the work in mechanical drawing and presents enough of the elementary principles of design, including the study of strength and stresses, to enable the apprentice to have a rough conception of the principles underlying the methods of determining the conformation of machine parts. The work is not intended to produce designers, but to develop common sense with regard to the strength of machine or structure parts.

The work in shop management includes lectures upon shop arrangement, departmental and stock room reports, cost and time keeping, and economical methods of handling work. The course is intended to enable the apprentice to fall into his duties and his organization with intelligence and efficiency. Indeed, it is believed that this course of lectures is a necessary one for the young man whom it is expected to develop into maximum service to his corporation.

The texts for these courses of study have been largely prepared by the instructors in the apprentice schools and by the Pennsylvania State College. Before beginning the preparation

of the texts, a careful study was made of similar work prepared for other corporation schools and such published texts as were available. However, the texts themselves were written with direct reference to the kind of training it was desired to give in these particular schools. In obtaining the instructors for the schools, it was thought best to use college graduates who had had experience in the industries. Though it is difficult to find good men of such training for the salaries that are usually available for work of this nature, these schools have been quite succesful, and the instructing corps has proved itself to be efficient, both from the standpoint of the shop manager and the standpoint of the pedagogue.

Experience with these schools has clearly shown that the use of the proper principles of pedagogy in work of this kind is as important as in any other kind of school work. Indeed, this statement might be made stronger and revised by the statement that proper pedagogy is more important in this kind of school work than in most other branches of education. As a result, the employment of instructors who are not thoroughly capable from a pedagogical standpoint, however expert they may be in their own particular vocations, is a serious error and is bound to result in comparatively unsatisfactory results.

DISCUSSION ON "INDUSTRIAL EDUCATION" (REPORT BY EDUCATIONAL COMMITTEE), COOPERSTOWN, NEW YORK, JUNE 24, 1913.

Charles L. Clarke: The papers upon education which have been read this evening relate to industrial education directed toward the improvement in efficiency of the workmen in the various industries and the minor technical men connected therewith, all generally definable as laboring men, nevertheless of widely varying degrees of intelligence and skill. Hence, it is, specifically, vocational education.

The purpose is to make such men as a whole intelligently skilful in their calling, and therefore, more useful to their employers. Incidentally, it will result in a few men, with greater natural talents and force of character than their fellows, advancing from the ranks to assume executive positions of greater or less importance. Furthermore, it will undoubtedly vastly improve the relations between labor and capital, to their great mutual advantage.

It is not the speaker's purpose to traverse the matters relating to vocational education that have been presented in these papers except in one particular. The details can, obviously, best be handled by professional educators, who make a specialty of these lines of training.

Now, to the point that the speaker has particularly in mind—it is the teaching of good English composition, which has been referred to briefly in the papers by Mr. Rowland and by Prof. Jackson and Mr. Hale. Along with the study of matters vocational and cognate subjects, the study of English should diligently be pursued throughout the entire course, not merely in a formal way, as determined by the educators, but through notes and examination papers handed in at frequent intervals, which should be corrected by the English teacher and instructively commented upon before the class. Proper improvement and perfection in composition should be insisted upon, on a par with proper advancement in other studies.

Digressing for a moment from strictly vocational education, the study of English should be insisted upon in the student courses for graduates of technical colleges, which are now pursued in the works of some of the large manufacturing corporations. Deficiency in ability to write good English (which includes, of course, correct spelling) is nowhere more apparent than among young men just out of college, and this defect does not wear away any too rapidly with the progress of the years.

It is a serious handicap to them, and especially to skilled but uneducated artisans, who are liable keenly to feel this defect which the speaker has often observed, like a weight bearing them down and making it appear to them useless to try to rise above the lower level in which circumstances have placed them.

Drill the artisan in good English, make him conscious that he can talk and write with respectable correctness. It will conduce

to clearness and conciseness of expression, which are most important adjuncts; will help discipline his mind and make him a clearer thinker, besides increasing his self-respect, all of which will make him more valuable to his employer and also to himself.

A professor of rhetoric in Harvard University has stated in his text-book on the subject that although there may be good English there is no such thing as perfect English. Therefore, an effort to reach the unobtainable may not be made; perfect English is practically out of the question; the English of the scholar is unnecessary; nevertheless, ability to speak and write passably good English should play a serious, substantial part in vocational education.

Henry G. Stott: It seems to me the keynote of the whole situation in regard to industrial education occurs just in a single sentence in the paper by Prof. Jackson and Mr. Hale, with which I heartily agree. It is as follows: "It was, therefore, very carefully determined at the outset that the apprentice school work should be so given as to develop in the young men a proper ambition to become skilled in work of this character and at the same time to avoid developing in them the discontent and unhappiness which comes to those whose aspirations are beyond their capability or circumstances—as would be the case if they were led by their instructors to believe that they should attain positions in which manual skill and labor is not required."

It seems to me that is the keynote of the whole situation and it points to a grave danger in this so-called trade school and industrial education by corporations. The company with which I am connected has done a good deal of this work, but we do it mostly with a view of finding out what the men know, so as to be able intelligently to select men for promotion. We fear there is a very great danger, as noted here, of storing up in men false ambitions and false ideals such as that it is not quite as honorable or as reputable for a man to work with his hands and have a suit of overalls on, as it is to have a clean job as a clerk at $50 or $60 a month, and there is a tendency, especially with the young foreigners, to set up these false ideals as to the value of education.

I do not wish to underrate the value of education, because no one can get too much of it, but a great many of our high schools seem to teach wrong ideals in many cases, and I believe the whole secret of success is in finding out which of the men are ready for promotion, and which of the men really deserve to be promoted, and not in the attempt to give them a smattering of instruction in a few subjects. We know, when it comes to engineering work, that we must have men who are thoroughly trained in the fundamentals of physics, and we select our engineering group from college men, as in the company I am connected with, but before promoting our men to the minor positions of responsibility we use the training schools to find out which of the men are thinking seriously. Perhaps once a year we find a man who should be encouraged to try to work his way through college, and we help

him all we can. Three or four men in the last three or four years have made very creditable records, but that is a very small percentage, probably less than ¼ of one per cent of the employees, so that I think the point of view announced here in the paper by Prof. Jackson and Mr. Hale is really the keynote of the whole situation—that we must be careful not to store up false ambitions in a man who is incapable of being promoted, because he has not the ability or the necessary education, and it is distressing to see him become discontented and unwilling to work at honorable trades at which he could earn three or four times as much as a clerk makes. The result of this dissatisfaction is that he goes out into clerical employment, and he finds that he is in the midst of a host of competitors for what he calls a clean, respectable job.

M. T. Crawford: In my connection with the public utility company in one of the Western cities, I have found that there are many young men at work during the day in the city, who would like to study further. I would like to bring out in a little further detail the work which is accomplished by the universities in some of these far Western cities.

The University of Washington, in Seattle, for instance, gives a course in electrical engineering covering four years leading to the degree of B.S.E.E. and with the fifth year giving a degree of M.S.E.E., and after three years in a responsible position the degree of E.E. is given. In addition to this regular college work, night classes are held for advanced study and research work by technical graduates who are engaged in practical work during the day in the city. Separate night classes are also to be given this coming year of a more elementary nature for men who have not completed the University courses, but who have met the requirements of the University, who have to work during the day. The latter are standard courses and University credit is given for the work. A considerable amount of special work has also been done by the regular students from time to time for the larger companies, such as oscillograph tests and special research work, which gives them a direct practical contact with operating conditions.

J. W. L. Hale: The apprentices serve four years and are moved from one department to another as stated in the paper. This is done so that they may have a varied experience. We feel that we lose nothing by giving them a broader idea of the work in the several departments of the shop as well as that in which they are more directly interested. Many of these apprentices will ultimately be called upon to fill positions of minor responsibility in shop management, and therefore this knowledge of other departments is necessary.

I might say along the line of the questions which have been raised that apprentices, when they go into the school, have open to them all of its privileges and they are bound to make improvements along general lines. However, the matter of education of apprentices, as it appeals to us largely, is in regard

to developing their powers to comprehend instructions which are given them and to make reports properly, etc., etc. You appreciate the necessity of this in the operation of a railroad. It is necessary that they have such a knowledge as will enable them to understand instructions and make reports intelligibly.

Regarding the aspirations of apprentices for something higher than that for which they are suited, I have spoken of our schools as selective media. The boys who come to us are of all grades of ability, and it is for us to line them up and put them into that part of the organization in which they properly belong.

So far as our experience extends the boy has not become dissatisfied with his condition through the fact of further instruction. We think a great deal depends on the instructors as to the ideals which they put before the boys. If they teach them the honor of labor, and instill in their minds that, by attention to their duties, promotion is open to them, and that some of the railroad mechanics earn more than professional men, it seems to me that this difficulty can be overcome to a large extent.

The Pennsylvania Railroad is only one which has taken up the matter of an apprentice school instruction system. There are at least eight, and possibly more, representative roads that are engaged in the same work. These extend from the Atlantic to the Pacific, and the work is progressing very rapidly. This is one of the principle features of work which is being taken up in the new organization, the National Association of Corporation Schools. The matter of corporation industrial education is not new but is well afield.

J. Lloyd Wayne, 3d: I believe in all matters of this kind the difference between success and failure may lie in the local traditions of the community in which you are situated. For instance, in the East, where both a man and his family will undergo considerable personal hardship to give him an education, you can go a great deal further in this matter of education than you can in a community where practically none of the families will undergo any hardship to have their young people go beyond the education which is required by law. If you try to introduce industrial education or similar activities amongst people of that kind, you are apt to run up against this condition which I have seen,—many of the men will feel that to join these classes gives them a pull to get ahead. Some of them do not, of course, but I have known of a school where it was discovered a large majority of the pupils attended with that motive in view, having no motive for attendance except the standing which they felt attendance at the school gave them with the boss. They really did not get much out of it and the school was abandoned.

This state of mind on the part of the pupils was found to be not exceptional, but quite general. One whose experiences have been gained in the East exclusively is likely to overlook the fact that in a relatively young country there is not much ambition to secure an education, and more people are satisfied to work along a

certain number of prescribed hours, and have their endeavors end with that, rather than to take up any additional work in the form of study.

A. M. Buck: Although we have been talking this evening almost entirely about instruction, I think we have forgotten the instructor. In any scheme of industrial education he is one of the most important factors, and a careful choice should be made to secure the proper man for the work. In the college or university the instructor is often chosen because he was a good student, and perhaps has done excellent work after graduation. This, of course, gives no indication that he has the proper personality, or that he is especially fitted to instruct others. In some cases he may succeed, especially if his work be along the lines of research, where he does not come into intimate contact with students. When, however, we consider the choice of teachers in industrial or trade schools, I think the personality of the instructor is of vital importance, and believe that it is absolutely essential to choose men for this work who are in close touch with the situation. Furthermore, they should be able to inspire the men in their charge. I have had but little experience with vocational training; but I do know a number of college professors who have given inspiration to their students and brought out a great deal more work from them than is ordinarily obtainable.

Another point which comes up in this connection is the training of the instructor. In many cases he is simply turned loose on his work without having had any special training, and often without definite instructions of any kind. The necessary training is not given in many of our technical schools, but I believe it should be. At least the instructor should be told exactly how to go about his work to produce the best results. I think many instructors who might be very successful fail because of their inability to appreciate the situation. Had they been properly directed at the beginning, and understood thoroughly the proper attitude toward the students, as well as how to impart their knowledge, much good might have resulted both to themselves and to their students.

F. C. Caldwell: Much has been said this evening about the value of vocational training as given by industrial concerns, as a help in the selection of men to do the work for which they are best fitted. The two aspects which this work seems to take on are these: first, the work of the industrial concerns in training their own men, and second, the work of the universities and other institutions in training those who either are not yet connected with any manufacturing concern, or in training those who are so connected during their spare time. There is one point, that I was glad to hear Mr. Stott speak of and which needs to be emphasized; that is the importance of being on the look-out for the unusual case, for the ¼ of one per cent, that is for the man who ought not to remain a mechanic, but who ought to be encouraged to go ahead and secure a college training, so as to become an en-

gineer and a leader. We need all of this type of men that we can possibly secure. The supply now is not equal to the demand. It may not be generally known that the supply of college-trained engineers is decreasing, while the demand is increasing; that throughout the country the engineering colleges have not been increasing in the number of their students during the past four years and in many cases they have actually decreased. This is largely due to the growth of the agricultural colleges and general development of the agricultural movement. We therefore need in our engineering colleges, all of the men that we can possibly get, that are of the right kind out of which to make engineers. This is one of the things which vocational training in industrial concerns should accomplish, the picking out of the exceptional man, who is just the man to send through college, to receive a course in engineering, and to be turned out as a competent engineer.

The other point is the work being done in the line of vocational guidance outside of the industrial concerns. There are, as you may know, societies in many of the larger centres whose object is to study the subject of the vocations in which the boys and girls may engage, and to try to guide them into those vocations which will give them the best use of their abilities and yield the greatest return to society from the results of their endeavors. We know that there is a tendency for the boy, when he leaves school, to pick up some stray job like selling tickets for a moving picture show or something of that sort, which will yield him some money immediately, but which leads to absolutely nothing in the future, and the object of the vocational guidance societies is to try to educate the school children into the idea of looking forward to their life's work and planning for it, even before they have left school. It seems to me that this is a very important feature of this work which our committee might do well to consider.

H. M. Friendly: There is a phase of education which I think has been sadly neglected in colleges and in various institutions of learning, and that is encouraging the students in the reading of technical magazines and periodicals. You cannot impart experience to a man, but you can impart knowledge to him in various ways—by reading periodicals and other literature, and reading the experiences of men who have superior ability to observe phenomena, etc. A man will often get in touch with practical matters, and gain a degree of experience in reading about them, possibly better than he might by actual contact with the work. With all due respect to the colleges, I have had occasion to observe that the men they turn out, or at least most of them, are deficient in that one thing, and I also find that many of the men that come out of the colleges and other educational institutions, because of their failure to read technical literature, fall by the wayside.

Mr. Carron: There are two or three points upon which not enough emphasis has been put in the discussion of the papers this evening, and one of these points is, in order to make real progress in educational matters the fundamental principles of educa-

tion must be applied to these vocational courses just as they are to the more advanced courses, and a great deal of the fault in the past with vocational courses, which have sprung up here and there, is because they have not been carefully organized, have not been put in charge of men who have made a study of educational problems, and the result has been these various deficiencies which have been pointed out. In one class the instructors try to instill too great an ambition in the minds of the students, and succeed in getting them discontented with their particular line of work and more harm than good is done. In another class the instructors do not appreciate the advantage of picking out the occasional individual and giving him the personal instruction which is needed; but the fact that a group of papers of this sort is brought up for discussion at a meeting of this nature and the fact that more attention is being given to the subject along these lines is encouraging to us who are interested in educational problems.

George C. Shaad: I wish to take some exception to the points brought out in regard to the matter of the care now being taken in selecting instructors in all classes of educational work. I believe the personal side of the instructor is receiving, in the better grades of institutions, as much, if not more, attention than the purely theoretical knowledge which the particular candidate may possess. It is only by securing coöperation and one institution profiting by the failure of another that much can be done through these organizations for industrial education, and if these institutions will profit by the failures of the past as much real progress in this line as in any other line of education can be made.

O. J. Ferguson: There is an unfortunate thing which develops in the course of the instruction of college classes, and that is that some 30 per cent or perhaps 50 per cent of the men in the classes ought never to have gone to college. I believe that one of the most encouraging features for those who are taking up the matter of vocational training is to be looked for in the possibility of the selection of our raw material. I believe that if we were able to make the selection of the raw material when it comes to us, rather than taking a great deal that should not be allowed there, the results that are attained from college education would be greatly improved as well.

Comfort A. Adams: My interest in the subject before us is not so much that of the professional educator as that of the citizen and engineer, and the point I wish to make relates to certain broad aspects and ideals of social and educational efficiency.

In the youth of our country we have the raw material which undergoes some degree of refinement and adaptation to useful ends, in our various educational institutions. The varieties are only limited by the number of individuals, some are fitted by nature for one life task and some for another. To make the most of this raw material is the problem of education, and the degree in which we succeed in wisely *sorting* it and then in *developing* it in each of the numerous fields of service to its maximum

usefulness, is a measure of the real efficiency of our educational system.

The problem of developing such material as now comes to our various schools and colleges, and the increase in the variety of fields in which education is offered, are common subjects of discussion, but it is to the subject of *sorting* that I wish to call your particular attention.

For the purpose in hand let us divide the youth of the country into two groups: one group including those to whom the higher or professional education is now open—less than 5 per cent of the total—and the other group constituting the remaining 95 per cent. Some may disagree with my figures and say that every really strong young man has this opportunity if he is willing to work; but such are the rare exceptions and I am talking of averages. If the rare exceptions were alone to be considered, the problem of education would be a simple one. Actual statistics will show that my 5 per cent is a very liberal allowance.

Within this small group there are many who are not able to profit by their opportunities and who are, as a result of professional training, actually unfitted for occupations more adapted to their native ability, such occupations being considered beneath a college man. On the other hand, there is undoubtedly much material in the larger group well able to take full advantage of the highest educational opportunities, but prevented from so doing by no fault of its own. All this is a great burden upon and loss to society, a burden in attempting to instruct the unfit, and a loss by the waste of much good material sent out into the world without appropriate training. A young man's college tuition fee pays ordinarily not more than one third of the cost of his instruction; the other two thirds is contributed directly or indirectly by the community at large, except in the case of state universities where *all* of it is so contributed. Thus all of those young men who are not profiting fully by this training, who are not being really educated (and this number is not small) are burdens on the community, even though they are paying tuition.

The industrial training here under consideration, is a good thing because it offers to those in one group an opportunity to increase their efficiency within that group, but it does not fundamentally change the situation or touch the root of the real difficulty. It does not appreciably increase the opportunity for the passing from one group to another better adapted to the native capacity or ability of the individual in question, it does not appreciably improve the "sorting" process.

I grant you that this difficulty is a fundamental one and that it is entangled with the very roots of our social order, but it is well occasionally to realize the defects of that social order and to turn our eyes towards an ideal if one is available. The nearest approach to a solution of the problem lies in what might be called the competitive system of education, in which the degree and variety of education open to any individual is *wholly* dependent

upon his ability to profit by the opportunity, as determined by competition. (I here use the word "education" in its narrow rather than in its broad sense). A somewhat distant approach to such a system is now in operation at West Point and Annapolis. Under our present social order, educational opportunities beyond the legal requirement of a primary schooling, are largely dependent upon the length of the parents' bank account. In other words, the present basis of "sorting" our "raw material" is most crude and irrational.

Mr. Stott speaks of the danger in the proposed system of industrial training, that some young men may be educated beyond their ability to make good or to profit by it. This is exactly what I have tried to point out in connection with our present system of higher education, except that it is vastly greater in the latter case owing to the fact that many men are in college largely because of the money back of them, whereas, the men in the various industrial or apprenticeship courses are usually on their merits. It has also been stated that men attend these courses in order to "stand in" with their employers or bosses. A boss not able to judge of a man on his merits is hardly fit for his job. But in the college this becomes a real danger. A boy from a well-to-do family is sent to college and is made to feel that he must follow some "profession," when in fact he is not fitted by nature for any of them. He may be a good mixer, he makes friends and connections in families of wealth and is boosted and pulled along into positions which he fills with little satisfaction to himself or anyone else, while thousands of men with the ability and character which he lacks, are wasting that ability and making poor manual laborers for lack of educational opportunities. This all means social waste and inefficiency. We too rarely stop to realize that the more nearly each unit in a social group can be developed to its maximum usefulness, the better off will every other unit be.

Let us then lend our hearty support to any step which extends our system of vocational training, which broadens the range of educational opportunity, but, let us at the same time remember that with ever so varied a range of offerings, we are yet a long way from any reasonable social efficiency if we say to this or that class in our society, you may be educated only in this field, these other opportunities are closed to you.

Briefly, we must pay greater attention to the "sorting" of our raw material.

Harry Barker: There are two matters which have been mentioned, the one by Professor Caldwell and the other by several members. Professor Caldwell spoke of the work of vocational guidance which has been started in a number of places, and the others have mentioned the need of weeding out unfit men in college courses, and in vocational courses to a certain extent. These two things may go hand-in-hand in the elementary public schools. A start has been made to carry out such work along

psychological lines, but so far the work has largely been along economic improvements. There are ways in which you can detect abilities, tendencies, bents, etc., but only a few people in the country have any real knowledge which can be brought to bear practically on this matter. Yet a start has been made and it is well for engineers to keep in touch with this particular phase of vocational guidance. The one man in the country who can speak with greatest authority on this phase of vocational guidance is Professor Muensterberg, and he is going into the matter seemingly very deeply. He seems desirous of sharing the results of his studies and has published many details of his procedure.

The ways in which we can detect budding ability and bent or trend towards certain qualities need to be considered along with bureau work which makes vocational guidance stand for certain economic improvements. We do not want to lose sight of mental scrutiny in the great stress which is being put upon industrial opportunities.

Arthur J. Rowland: The general topic for the present report of the Educational Committee is "Industrial Education." This is also carried at the heading of each page of my part of the report. It was not my intention to limit what I had to say to that education which trains men in industry or in the industries; but rather to consider education planned to train those working in the industries for wider usefulness, and for higher places. Relatively little of what I have described has for its aim the training of routine workers; the object is rather to develop intelligent understanding of why a given routine method is used, and the principles behind it, along with an appreciation of the relation of science and technical subjects to everyday affairs. Such training fits a man for greater usefulness with the corporation for which he works in the position he holds; and also makes him available for advancement to places of higher responsibility. The interest most corporations take in the education of their employees seems to center on this last fact. A man who is worth anything, who has been tried out in a humble place where his personal qualities have become known, is preferred for advancement to a higher place, if educational limitations are not too great, above the one who comes in unknown and untried.

The scope of the paper has been limited to that education offered to men who are employed and to the subjects which have to do with industrial and technical training. In my paper I have not attempted to deal with this subject exhaustively. I have not included every school in Philadelphia and vicinity. I may not have done justice to the evening school work of the Public School System of Philadelphia. The statements made near the top of page 1435 are based on the fact that except for trade school courses the subjects offered are, almost all, those belonging to *regular* high school work. The city of Camden, N. J., just across the Delaware River, has taken hold of the prob-

lem of industrial education in a very careful way through its Superintendent of Public Education, and is now giving evening instruction in wood, metal working, and in elementary mathematics. Certain firms have been, in a limited way, undertaking instruction (of the school kind) for their employees.

At this present time I believe it is safe to say that nothing has been done in Philadelphia in the way of "continuation" school work except as noted in the last section of the Committee report in certain of the Pennsylvania Railroad shops. There is a pretty strong feeling among Philadelphia educators interested in vocational work that continuation schools may be all right in Germany; but that this kind of work to be successful must be limited to countries where class distinctions are closely drawn and the highest aim in the education of a worker is therefore to make him thoroughly skilled in his own line and sufficiently intelligent to find "joy in his work." In America every man is pushing for higher places in the shop and in the social scale; for better and fuller recognition of his best capabilities. Such a condition is fundamental in a democracy like ours and all education should take account of it.

In my paper I call attention to the fact that in Philadelphia the various schools have each developed the kinds of education they offer, and the subjects of instruction they are prepared to give, in a thoroughly individual way. This has a certain kind of merit. It also has some serious faults. Since the paper was written an effort has been made to associate all the institutions offering evening instruction in technical subjects, especially those relating to engineering, for purposes of better mutual understanding and in order to afford a means of dealing with the educational problems of our city in a direct way as a unit. The advantages of cooperation have already been felt and during the summer it is probable that much will be done to correlate properly all this work, to associate it with needs and wishes of manufacturers and corporations, to have it properly understood by the general public. It has developed that there is as much value to be gained by educational institutions who come into close association in a definite organization as there is by manufacturers and business men in their trade organizations. At the present time in Pennsylvania there is a good deal of stir about educational matters, especially in relation to those who have not had or cannot have the advantages of the standard forms of education. The organization of Philadelphia schools, etc., just referred to, is likely to become identified with a state-wide movement for educational uplift.

A tendency of our day is to establish many kinds of schools and many subjects of instruction, especially in industrial and technical lines. I believe there is danger of creating too many. The newer kinds of vocational training proceed from the concrete to the abstract; from practise to theory. This leads to all sorts of trade instruction as fundamental. The number of trades is

almost limitless and the fundamental principles connecting with them are relatively few. A little vocational guidance work would show workers and those interested in their education the need of instruction in principles, and much more than in practise. Many illustrations might be given, but I will not take time for them. Planning mainly for the teaching of principles, a few classes only for which there was large demand might be organized. A constantly increasing number of specialized classes offering new problems in teaching and new requirements in text-books would be avoided.

Corporation schools are beginning to attract considerable attention. Specialized instruction will always be required in every business and industry in order to qualify its workers to meet its individual problems well and intelligently. Such instruction the school cannot give, since each of its classes has members from among the employees of many corporations. On the other hand, the corporations cannot plan to teach principles and general subjects, which are fundamental and necessary prerequisites to intelligent specialized instruction, unless they duplicate the equipment and faculties of existing schools. Since such schools commonly require heavy endowments or state appropriations in order to operate, the expense to a corporation (if the work is well done) is prohibitory.

Many societies claim to have educational work in connection with their monthly or bimonthly meetings. This always takes the lecture form and is "smattering" in character. Its value is much over-estimated. A man doesn't know a technical subject unless he can talk on it himself and work out problems connected with it. This can be secured only by *systematic* training accompanied by recitations under a teacher.

Correspondence school work is also of small value. Unless supplemented by direct instruction, and, in many subjects, by opportunities to conduct personal experimental work, not much can be learned. The experience of most evening schools with correspondence school students who seek them proves this.

Referring now to the paper, at page 1421, we find my feeling about evening school work, based on twenty years of experience in it.

In training workers for wider and higher usefulness in their chosen vocations, the education must be restricted in scope; given by an experienced teacher who can respond to the difficulties of his scholars; and must be laid out so that a worker in a humble place can be trained for a position higher up, attaining which, the training for something still further on can be secured, and on and on indefinitely. Such opportunities are being developed more and more in evening school work in Philadelphia. The same thing could be done in part time schools of a "continuation" type, and it is hoped that somehow this will be tried out in the near future.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

(1) SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE SUSPENSION INSULATORS

BY F. W. PEEK, JR.

The insulators specified herein are to be of the link suspension type for use in a..... volt circuit. The dielectric must be homogeneous, symmetrical, and not appreciably warped.

Surface of Dielectric:

The entire exposed surface of the dielectric must be smooth, uniform, and impervious to moisture. The dielectric must be moisture-proof throughout, and in case a glaze is necessary on the surface it must be smooth, hard and firm, and uniformly applied. The dielectric surface of the insulators must be durable and unaffected by the weather, ozone, nitric acid or nitric oxides, or sudden changes in temperatures over the atmospheric range.

The requirement for imperviousness shall be as follows:

The sample for test must not have a glazed surface, and the volume must be in the neighborhood of 2 cu. in. (30 cu. cm.). It must be dried at 120 deg. cent. until weight is constant, and then immersed in water for 48 hours. The temperature of the water to be between 20 and 40 deg. cent. It is then removed from the bath, the surface water rubbed off with a cloth, and weighed. It must not have absorbed water to the extent of more than 0.25 per cent of its original weight.

Cement:

When cement is necessary in assembling the dielectric and metal parts, it must be strong and durable—not the weakest point—and should preferably be rendered impervious to moisture,

unaffected by changes in weather, ozone, nitric oxides, or sudden changes in temperatures over the atmospheric range.

If the cement contains organic compounds, the flow point must be over 90 deg. cent.

Fragility:

Designs must be of rugged construction and so formed that there will be a minimum exposure of any fragile part to missiles from below.

Length of Complete String:

Total length of complete string of units including cable clamp should not be more than— ft. (—cm.), nor less than— ft. (—cm.)

General Design:

Practical considerations being equal, preference will be given to the design applying best scientific principles in regard to the dielectric circuit.

Tests

Factory Test:

Every single disk or unit shall be tested for two minutes continuously with the voltage held at 10 per cent below the arc-over point.

Three completely assembled samples of each type of insulator to be considered shall be subjected to the following tests, and the purchaser reserves the option to subject one out of every two hundred to the same tests.

Arc-Over Tests:

The complete insulator or assembled string shall have a sufficient number of disks in series so that while dry the arc-over potential (effective sine wave) shall not be less than three (3) times the operating voltage (between lines), and not less than 2½ times the operating voltage when exposed to a spray at an angle of 45 deg., giving 0.2 in. (0.5 cm.) precipitation per minute.

While under the above rain test the insulator must be able to withstand a continuously applied potential of 2¼ times the operating voltage for five minutes. The specific resistance of the spray water must be between—and—ohms per cm. cube. These potentials shall be supplied by a 60-cycle testing set, giving approximately a sine wave.

Throughout these electrical tests the string of insulators is to be supported on a grounded metal arm, and the voltage is to be applied between this arm and a 6-ft. (2-m.) length of cable

—the same as is to be used on the transmission line. This cable is to be gripped firmly in a clamp, and to project three ft. (1 m.) on each side. The potential shall be applied at not over half arc-over voltage, and increased at the rate of about 1000 volts per second.

Arc-Over String:

Arc-over should take place completely across the string, and not from unit to unit in cascade. Preference will be given to the insulator which most closely fulfils this condition.

Corona:

At 1.3 times line voltage there must be absolutely no sign of corona or static discharge on either the insulators of the assembled string, or any of its fittings. Other conditions being equal, preference will be given to the insulator for which the corona starting point is nearest the arc-over point.

Voltage Balance of String:

The ratio of the measured arc-over voltage of the string to n times the arc-over voltage of a single unit shall be determined, n being the required number of units in a string. Competitive tests must be made at 60 cycles and on the same transformer and generator. Insulators are to be supported from grounded metal arm as above, and arc-over voltages measured on string lengths of from one to n units. Other conditions being equal, preference will be given to insulators showing best balance along the string.

If, in the opinion of the engineer, the "multigap effect" at high frequency, on account of large metal parts or for other reasons, is probable, a special high-frequency string arc-over test may be called for.

Uniformity Test:

Twenty-two single disks or units taken at random from stock, and which have passed factory test, shall each in turn be placed in oil, potential not exceeding half arc-over voltage shall be applied, and gradually increased at the rate of about 1000 volts per second until puncture shall occur. Any twenty of these puncture voltage values shall then be selected. The difference between the maximum and minimum puncture voltage must not be more than 20 per cent of the average voltage. The average puncture voltage must be not less than 30 per cent above the dry arc-over voltage.

Special Test

Impulse Test:[1]

Twenty-two units shall be selected at random. Each of these disks shall be connected in turn to the impulse circuit shown in Fig. 1. The gap *A* shall be set (60 cycles) at three times the arc-over voltage of a single unit. The voltage shall be increased until gap *A* arcs over, when the circuit shall be immediately opened by breaker. This shall comprise a "stroke." . . . . strokes shall be applied to each unit, or until puncture occurs. Preference shall be given to the insulator showing the greatest uniformity and the highest average puncture voltage. Referring to Fig. 1, the shunt condenser capacity shall be— microfarads, and the inductance—— millihenrys.

Note: The above test will show, in a general way, the probable effect of surges, lightning, etc., on the life of the insulator, as well as uniformity of the porcelain. The number of strokes, and

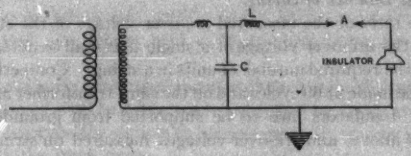


Fig. 1

the voltage to puncture, will depend upon wave front of impulse, on frequency, etc. This cannot now be definitely specified, as the phenomena have not yet been sufficiently investigated. A test as above, however, is very important in competitive tests.

Method of Measurement:

Unless otherwise specified, the tests are to be carried on and voltages measured by the sphere gap, as proposed for the Standardization Rules of the American Institute of Electrical Engineers. The voltage shall be controlled in such a way as not to distort the wave form. It is preferred that it be controlled by a regulator consisting of a shunt resistance directly across the low-voltage side of the transformer, and a series resistance in the supply circuit. The shunt resistance must always by-pass at least five (5) times the exciting current of the transformer. The

1. See *High-Frequency Tests of Line Insulators*, by Imlay and Thomas, Trans. A. I. E. E., Vol. XXXI, 1912, p. 2121.

principal control is effected by the series resistance. This method is often spoken of as a potentiometer method.

The sphere gap voltmeter must be corrected for temperature and barometric pressure. A water tube or non-inductive metallic resistance of about one ohm per volt of test voltage should be placed directly in series with the gap. The arc-over voltage and corona-starting voltage must refer to the average barometric pressure where the insulators are to be used and at a temperature of 25 deg. cent.

Mechanical Stress Tests:

After it has been decided from the electrical test how many disks shall constitute a suspension unit, this number shall be attached in a string, together with the adopted suspension hook and cable clamp, and a load[2] of —— lb. (——kg.) shall then be applied without rupture or signs of distress in any part of the string.

Mechanical Inspection:

A mechanical inspection shall be made of all insulators and those shall be rejected which contain open holes or cracks in the glaze or porcelain, or are not perfectly cemented. The inspector shall use a light-weight mallet to rap each part and note the soundness of the ring. Occasional samples of the ware shall be broken to see that they do not contain air cells or foreign matter.

Protection of Metal Parts:

Metal parts must be made of non-corrodible metal or be heavily galvanized.

General

The insulator makers shall be required to furnish all facilities, equipment, and labor for making tests and inspection, as specified above, and shall at all times allow free access to such facilities and equipment by the authorized representatives of the purchaser until the entire order is inspected.

2. Depending upon the size of the conductor to be used and the wind and ice load allowed.

(2) SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS

BY J. A. SANDFORD, JR.

Specification for Suspension Type Insulators

General:

(a) These specifications are intended to cover the design, quality and manufacture, including inspection and testing, of .....porcelain insulators, cat. No.....

(b) The operating voltage will be.....

(c) There will be required approximately.....suspension insulators, each of which shall consist of.....units.

(d) There will be required approximately.....strain insulators, each of which shall consist of.....units.

Metal Parts:

All cap castings intended for cementing to the top of the porcelain parts shall be of the best grade of malleable iron. All studs or center pin forgings intended for cementing into the hole in the under side of the porcelain unit, shall be of the best grade of steel forging.

Galvanizing:

All cap castings and center pin forgings shall be galvanized by the hot dip process, and must be capable of standing the A. T. & T. immersion test for one minute. All fittings failing to meet this test shall be rejected.

See separate specifications covering galvanizing in detail.

Porcelain:

All insulators shall be made of a dense, homogeneous porcelain best adapted to high-tension insulator requirements, free from

injurious cracks and flaws or other injurious defects that would render them unfit for the purpose intended. The burning of all porcelain sections shall be done so as to insure thorough vitrification.

Glazing:

Unless otherwise specially agreed upon, the glazing will be brown and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement.

Absorption:

Porcelain shall be practically non-absorbent. A test section broken from any insulator shall not show an absorption of more than one tenth of one per cent of its weight.

Electrical Tests before Assembly:

After inspection to eliminate faulty material, the unassembled porcelain disks shall be given a regular routine electrical test at a point just below flash-over potential for five minutes. If puncture occurs in the fifth minute, the tests must be continued until no puncture occurs in one full minute of test. All parts failing to meet this test shall be rejected.

Assembly:

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, throughly mixed, and the proper stiffness for the nature of the work. The assembly shall be so done that no hollow or voids will be left between these cemented surfaces and all superfluous cement must be cleaned off of the insulator before crating.

Mechanical Test:

After approximately ten days' setting of the cement, all units shall be given the regular routine mechanical test of —— lb. (—kg.), with tension applied in line with the axis of the insulator.

Final Electrical Test:

All units shall be tested electrically to 95 per cent of flash-over for one minute.

Design Tests:

The dry arc-over value of the assembled insulator, consisting of——units, shall be not less than—— volts, potential applied for one minute.

The wet arc-over value of each insulator, consisting of —— units, and tested under standard precipitation of 1 in. (2.5 cm.)

fall in five minutes at an angle of 45 deg. with the horizontal, shall be not less than——volts.

At the option of the purchaser or his engineer, the contractor shall conduct tests to demonstrate the dry and wet flash-over values given above, but inasmuch as these tests are for proving correctness of design only, not more than five insulators of the same design shall be required to be subjected to the tests.

The average ultimate mechanical strength of the insulator shall be not less than 8000 lb. (3630 kg.).

At the option of the purchaser or his engineer, one tenth of one per cent of the number of units so covered by these specifications, may be tested to destruction, but only such units as are rejected for other causes shall be used in making this test.

Inspection:

The contractor will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at contractor's pottery.

The inspection or waiving of inspection will not relieve the contractor from obligation to furnish material in accordance with specification.

Crating:

All insulators shall be assembled and packed one per crate ready for suspending from the towers. The crates will be of the contractor's standard design.

Should the contractor's design of crate not be satisfactory to the purchaser or his engineer or inspector, contractor will change same to suit the purchaser's requirements, with the reservation that at the contractor's discretion he may or may not still assume the responsibility for the safe transportation of the material affected by the change. Further, should the revised crate specified by the purchaser, his engineer or inspector, cost more than the contractor's standard crate, the difference shall be charged to the purchaser, which difference in accepting these specifications the purchaser agrees to pay.

Drawings:

Drawings showing detail of units and spacing of units in complete insulator are herewith submitted.

Specifications for Pin Type Insulators

General Information:

(a) These specifications are intended to cover the design, quality and manufacture, including inspection and testing, of .....porcelain insulators, cat. No.....

(b) The operating voltage will be.....

(c) There will be required approximately.....insulators made up of.....parts, catalog No.....

Porcelain:

All insulators shall be made of a dense, homogeneous porcelain best adapted to high-tension insulator requirements, free from injurious cracks or flaws or other injurious defects that would render them unfit for the purpose intended. The burning of all porcelain sections shall be done so as to insure thorough vitrification.

Glazing:

Unless otherwise specially agreed upon, the glazing will be brown and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement.

Absorption:

Porcelain shall be practically non-absorbent. A test section broken from any insulator shall not show an absorption of more than one tenth of one per cent of its weight.

Electrical Tests before Assembly:

After inspection to eliminate faulty material, the unassembled porcelain parts shall be given a regular routine electrical test as follows:

All parts of the insulator before being assembled will be tested for..... minutes at the voltages mentioned below. Should any part be punctured in the..... minute of test, the test will then be continued until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two quantities of water.

The voltages to be applied to the several insulator parts will be as follows:

Head.....	volts
Second shell.....	"
Third shell.....	"
Center.....	"

All parts failing to meet the above tests will be rejected.

Assembly:

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, thoroughly mixed, and the proper stiffness for the nature of the work. The assembly shall be so done that no hollow or voids will be left between these cemented surfaces, and all superfluous cement must be cleaned off of the insulators before packing.

Final Electrical Test:

All complete assembled insulators shall be tested electrically at.....volts for three minutes. This test is to be applied in the same manner as the tests for parts described under "Routine Tests."

Design Tests:

The dry arc-over value of the assembled insulator, consisting of.....parts, shall be not less than.....volts, potential applied for one minute.

The wet arc-over value of each insulator, consisting of..... parts, and tested under standard precipitation of 1 in. (2.5 cm.) fall in five minutes at an angle of 45 deg. with the horizontal, shall be not less than.....volts.

At the option of the purchaser or his engineer, the contractor shall conduct tests to demonstrate the dry and wet flash-over values given above, but inasmuch as these tests are for proving correctness of design only, not more than five insulators of the same design shall be required to be subjected to the tests.

Mechanical Test:

The insulators covered by the specifications must be capable of withstanding without signs of distress a pull of 2000 lb. (910 kg.) applied at the tie-wire groove in a direction at 90 deg. with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

Inspection:

The contractor will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor,

etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at contractor's pottery.

The inspection or waiving of inspection will not relieve the contractor from obligation to furnish material in accordance with the specifications.

Packing:

All insulators shall be assembled and packed in..... each containing.....insulators. The.....will be of the contractor's standard design.

Should the contractor's design of..... not be satisfactory to the purchaser or his engineer or inspector, the contractor will change same to suit the purchaser's requirements, with the reservation that at the contractor's discretion he may or may not still assume the responsibility for the same transportation of the material affected by the change. Further, should the revised.....specified by the purchaser, his engineer or inspector, cost more than the contractor's standard..... the difference shall be charged to the purchaser, which difference in accepting these specifications the purchaser agrees to pay.

Drawings:

Drawings showing detail of the complete insulators covered by these specifications are herewith submitted.

Supplementary Directions and Explanations

Minimum Distance from Insulator to Grounded Objects:

As this factor does not enter into the commercial testing of insulators we recommend that it be neglected and the standard practise of the manufacturer accepted.

Number of Insulators to be Tested at one Time:

As there are several hundred sizes of porcelain parts to be tested we recommend that the number of parts under test at one time be such as to suit the manufacturer's convenience, except that the number shall not be so great as to take more than the full load current of the testing transformer, or make it impossible to hold the test voltage at the required point.

Factor of Safety—Dry:

We recommend that the dry flash-over voltage of any insulator be not less than three (3) times the normal voltage at which it is to operate.

Factor of Safety—Rain:

We recommend that the wet flash-over voltage of any insulator under standard precipitation of 1 in. (2.5 cm.) of water in five minutes directed at the insulator at an angle of 45 deg. with the horizontal, be not less than 175 per cent of the normal voltage at which it is to operate.

Quality of Water for Rain Test Purposes:

As this is one of the greatest, if not the greatest variable entering into the rain test, we recommend the use of condensed steam water. This can be easily obtained in any factory or laboratory. Pressure at 45 or 50 lb. (20-23 kg.) by means of an air pump completes an outfit that is satisfactory and the results obtained will be such that they will check very closely with those of other investigators.

Inasmuch as the results are comparative only, we feel that this is the best solution of the difficulty, even though the quality of the water may be slightly better than that met under operating conditions.

Angularity of Spray:

Standard practise has placed this at 45 deg. with the horizontal, the axis of the insulator being in the vertical postion. We see no reason for changing this practise.

Dew Test or Condensation of Steam on Insulator Surface:

We would recommend that this test be eliminated as giving no data that may not be obtained otherwise.

Testing Capacity of Equipment:

This is a matter of little importance so long as the number of insulators tested at one time does not load the transformer to more than its rated capacity, thus making it impossible to hold the voltage up to the required point, and may, therefore, be left to the manufacturer.

Method of Control of Voltage:

The method of using the field rheostat of the alternator as a means of control is offered as being the most desirable from all points of view. The low-tension winding of the testing transformer may be easily arranged so that for a given test voltage the generator may be worked at such a point on the saturation curve as not to cause any trouble from wave distortion, due to weak field excitation.

Control by means of an induction regulator taking current from a constant-potential circuit may also be recommended as

offering few objectionable features and as being very convenient in some instances.

Control by water rheostat in the primary circuit should be used only in cases especially arranged so that distortion of wave form will not occur or where much distortion will be unobjectionable.

The potentiometer method of control is well adapted to laboratory work where the number of tests to be made is comparatively small and the work is intermittent. For regular factory testing of insulators, however, this method is very expensive, due to the large amount of power being continuously expended in the resistances.

Grounding of One End or Middle of Testing Circuit:

As applying to all regular or routine tests this point may be left to the convenience or standard practise of the manufacturer. Special test or method of connection should be left for decision between the parties concerned.

Frequency of Test Voltage:

Any commercial frequency from 25 to 133 cycles, inclusive, may be used for regular factory routine tests. Special tests at frequencies not included above are to be covered by special specifications as occasion requires. This is intended to cover so-called "high-frequency or impulse tests."

Method of Measuring Voltage on Test Circuit:

The method of measuring the voltage on the test circuit shall be that method recommended by the American Institute of Electrical Engineers, covering such cases.

We suggest, however, that instead of taking spark gap readings for every test, the manufacturer calibrate his equipment, thus securing a curve between low voltage and spark gap readings which will be found to be sufficiently accurate for routine work and a very great time saver in making the tests.

What Constitutes Breakdown of an Insulator:

To the insulator manufacturer and probably the larger part of the engineering profession, "breakdown" of an insulator means failure by puncture, thereby totally destroying the usefulness of the insulator in question. We recommend that this term be understood in this sense.

Regarding corona, brush discharge, static streamers and arcovers we regard the conditions as different degrees of distress, and the manner of observing and recording them is open to discussion. The appearance of these various degrees of distress

is very irregular and uncertain and varies greatly on the same insulator with varying conditions of test.

The ultimate arc-over value of various styles of insulators may be obtained individually, but we recommend that the only way in which satisfactory comparisons of these other various degrees of distress on different styles of insulators can be made is to test all styles to be compared, at one time, in parallel, and in a dark room, when these differences can be seen and a fair record made.

Tests for the Puncture Strength of the Insulator:

Tests on a certain per cent of each 1000 insulators should be made to determine the ability of the insulator to resist puncture. This test is best made by submerging the insulator in oil. The nature of the test is such that it cannot well be specified to apply to more than a small percentage of the number of insulators covered by the specifications.

In testing suspension insulators under oil for puncture value, the porcelains should be completely assembled with the standard fittings, (or equivalent), with which they are to be used in service.

In the case of pin type insulators there should be attached, to the head of the insulator, wire representing the tie and line wires, and a metal pin should be assembled in proper manner in the pin hole.

The test voltage should then be applied to the fittings in each case. The average puncture value obtained under these conditions should not be less than 135 per cent of the dry flash-over voltage of the complete insulator in question.

In order to be able to compare results of tests made by different investigators, it is necessary to standardize the manner of applying the voltage as regards the time element involved. We recommend the following:

Apply to the insulator a voltage 20,000 volts below the dry flash-over value for 30 seconds, then raise the voltage by 10,000-volt steps until puncture occurs, holding the voltage constant at each step for 30 seconds.

For testing sample disks of porcelain not made up into insulator shape, we recommend that spheres ½ in. (12.7 mm.) in diameter be used as terminals.

Simultaneous Mechanical and Electrical Test:

We recommend that this test be eliminated from the list of commercial tests, as we feel that it is purely a laboratory proposition and that at best the results of such tests are very unreliable.

(3) INSULATOR TESTING SPECIFICATION FOR INSULATORS HAVING AN OPERATING VOLTAGE EXCEEDING 25,000 VOLTS

BY PERCY H. THOMAS

Introductory:

This specification gives the conditions of tests and inspections which are found best to secure reliable high-tension line insulators for use under the ordinary conditions of power transmission work. It is expected to serve as a skeleton or model specification and may be supplemented by such additional matters as may be appropriate for any particular case.

GENERAL SPECIFICATION COVERING ALL TYPES

1. (a) This specification is intended to cover the inspection and testing as to design, quality and manufacture, of ....., porcelain insulators, cat. No....., of ..... Company.

(b) The operating voltage is.....

2. *Drawings:*

A dimensioned drawing shall be furnished showing the complete insulator and, if the insulators are built up or composed of a string of elements, showing also each element.

3. *Inspection:*

The maker will give to the purchaser or his representative such access to his works at all times during working hours as is reasonable and necessary to determine the suitability of material to be supplied, and shall furnish all necessary apparatus, labor, etc., in making the tests herein called for without cost to the purchaser.

All insulators are subject to final inspection, test and acceptance at maker's pottery.

The inspection or waiving of inspection will not relieve the maker from obligation to furnish material in accordance with this specification.

4. *Design:*

All insulators shall be designed to fail by flash-over and not by puncture.

Insulators shall be of robust construction and design so as not to be easily injured in handling.

The ultimate criterion of the merit of an insulator is its performance in service and the best practical measure thereof is its behavior under definite tests. However, as no practicable tests actually reproduce service conditions, for example in the matter of high-frequency voltage, criticism on theoretical grounds is valuable, and, other things being equal, preference should be given to the insulators most closely conforming to theoretically best designs.

Metal Parts

5. *Corrosion:*

All metal parts shall be of non-corrodible material or shall be galvanized in accordance with the specifications for galvanizing prescribed by the joint committee of the National Electric Light Association in its specification for overhead crossings of power lines above telephone and other low-voltage lines.

6. *Factor of Safety:*

Metal parts shall have a factor of safety of at least three over the maximum strain that they may receive in service, except that with pins for pin type insulators the factor may be reduced to two where a higher factor is impracticable.

Porcelain

7. *Quality:*

All porcelain parts shall be made dense and homogeneous as is best adapted to high-tension insulator requirements, free from injurious cracks and flaws or other defects that would render them unfit for use in insulators. The burning of all porcelain sections shall be done so as to insure thorough vitrification. The surface shall be smooth and uniform and moisture-proof.

8. *Glazing:*

The glazing shall be ..... and of a reasonable uniform shade, smooth, hard and continuous over all surfaces except those to be in contact with the cement. It shall be unaffected by weather, ozone, nitric acid, nitric oxides, alkali dust, or sudden changes in temperature over the atmosphere range.

9. *Absorption:*

The requirement for imperviousness shall be as follows:

The sample for test must not have a glazed surface, and the volume must be in the neighborhood of 2 cu. in. (30 cu. cm.). It must be dried at 120 deg. cent. until weight is constant, and then immersed in water for 48 hours. The temperature of the water to be between 20 and 40 deg. cent. It is then removed from bath, surface water rubbed off with a cloth, and weighed. It must not have absorbed water to the extent of more than one-tenth of one per cent of its original weight.

Cement

10. *Assembling:*

All cemented joints between insulator parts shall be carefully made, using for this purpose the best grade of neat Portland cement, thoroughly mixed. The assembly shall be so done that no hollows or voids will be left between the cemented surfaces and all superfluous cement must be cleaned off of the insulator before crating.

Electrical Testing

11. *Wave Form:*

The wave form of the generator shall be true sine curve within the limits specified for generators by the Standardization Rules of the American Institute of Electrical Engineers.

12. *Control of Voltage:*

The voltage shall be controlled in a way not to distort the wave form. It is preferred that it be controlled by a regulator consisting of a shunt resistance connected directly across the low-voltage side of the transformer, and a series resistance in the supply. The shunt resistance must always by-pass at least five (5) times the exciting current of the transformer. The principal control is effected by the series resistance. The method is often spoken of as a potentiometer method.

For routine tests other methods of variation of potential may be used, provided such routine test apparatus has been calibrated by an approved method for the actual parts or groups of

parts to be subjected to the routine test. Such calibration shall be made on the maximum number of pieces to be used in the routine test.

13. *Measurement of Voltage:*

The method of measuring the voltage on the test circuit shall be that method recommended by the American Institute of Electrical Engineers, covering such cases.

For routine work, instead of taking spark gap readings for every test, the maker may calibrate his equipment by the approved method of voltage measurement, thus securing a curve between primary voltage and secondary spark gap readings, which curve may be used to determine the secondary voltage. Such calibration shall be made on the routine test apparatus with the maximum number of parts to be actually used in the routine test.

14. *Kilowatt-Ampere Capacity of Testing Apparatus:*

The kilowatt-ampere capacity of the testing apparatus is important, for the leading current taken by the insulators tends to distort the test voltage. The maximum current taken from the test apparatus should not be so great as to distort the voltage wave sufficiently to cause a condenser to take more than ..... times the current[1] it would take on a true sine voltage,[2] and the current taken from the test apparatus shall in no case exceed full rated load.

15. *Surrounding Conditions During Tests:*

With insulators intended for lines not exceeding 75,000 volts no object other than leads and support should approach nearer than 6 ft. (1.8 m.) to the insulator. For insulators intended for lines of higher voltages the conditions for the "design test" of complete insulators should be made as nearly as practicable the same as the conditions of actual service as regards the grounding of one side of the insulator and the arrangement and distance of grounded objects. A conductor of 6 ft. (1.8 m.) or more in length, extending equally on both sides of the clamp, should be used to represent the transmission wire.

Routine tests not being on completed insulators do not require these precautions, but in each case the method of making routine

1. See paper by C. M. Davis, this volume, p. 775.

2. This may be determined by the formula $I = n\,V\,C$, where I is amperes, V is volts, n is cycles per second and C is capacity in microfarads.

tests shall be calibrated when the surroundings are different from those here prescribed.

16. *Frequency:*

Tests should be made at the frequency at which the insulator is to be used. Where special agreement is made, tests must be made at 60 cycles on insulators intended for use on higher and lower frequencies. No error of a serious magnitude will be expected within the range of 25 to 133 cycles.

17. *What Constitutes a Breakdown:*

An insulator is said to "fail" under a voltage test whenever a puncture occurs in any part of the insulator or when a discharge of any sort passes from one terminal to the other, since such a discharge would be followed by an arc on a power line.

Local breakdown, either corona or local sparks, is an important symptom of weakness, and indicates possible bad performance under other conditions. The weight to be given local breakdown, however, is a matter of judgment and is best considered in the light of simultaneous competitive tests.

18. *Rain Tests:*

Water should be sprayed on the insulator at a uniform rate averaging 1 in. (2.5 cm.) depth in 5 minutes, and should be reasonably uniformly distributed over the whole insulator. The rate of precipitation shall be measured by collection of water in a pan at the location of the insulator, the insulator being removed. A satisfactory spray in the form of a fine mist can be obtained by some forms of atomizers where pressure is available.

The spray shall strike the insulator at an angle of approximately 45 deg.

The water used shall have a high specific resistance, not less than ..... ohms per cu. in. (..... ohms per cu. cm.). Pure water may often be obtained from condensed steam or melted ice, or rain.

When insulators are to be used in localities subjected to salt spray or alkali mists special tests should be made.

Oil Tests:

Tests on a certain percentage of each 1000 insulators, not exceeding $\frac{1}{4}$ of one per cent, should be made to determine the ability of the insulator to resist puncture. This test is best made by submerging the insulator in oil.

Suspension insulators should be completely assembled with the standard fittings with which they are to be used in service.

With pin type insulators there should be attached to the head of the insulator, wires representing the tie and line wires, and a metal pin should be placed in proper manner in the pin hole.

The test voltage should then be applied to the fittings in each case. The puncture value obtained under these conditions should not be less than 135 per cent of the dry flash-over voltage.

In making the test, apply to the insulator a voltage 30 to 40 per cent below the dry flash-over value for 30 seconds, then raise the voltage by steps, until puncture occurs, at a rate of about 1000 volts per second.

PIN TYPE INSULATORS

19. *Inspection:*

All parts should be inspected before assembling.

20. *Electrical Tests Before Assembling:*

All parts of the insulator before being assembled will be tested for three minutes at the voltages given in the following table. Should any part be punctured in the last minute of test, the test will then be continued until no puncture occurs in one full minute of test. These tests are to be conducted by inverting the parts in pans of water and placing water inside the several pieces, the potential then being applied to the two bodies of water.

TEST OF VOLTAGES ON PARTS

Head	volts
Second Shell	"
Third shell	"
Center	"

21. *Final Electrical Tests:*

All complete assembled insulators shall be tested electrically at 10 per cent below the flash-over voltage for three minutes. This test is to be applied in the same manner as the tests for parts described for Routine Tests, §§12, 13 and 15.

22. *Design Tests—Mechanical:*

The following design test shall be made on enough complete insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the behavior of the design and the uniformity of the product.

The insulators covered by these specifications must be capable of withstanding without signs of distress a pull of ..... lb. (..... kg.) applied at the tie-wire groove in a direction at 90 deg. with the axis of the insulator and pin. For the purpose of making this test, the insulator shall be mounted on the pin to be

used in service. In case of failure the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load.

23. *Design Tests—Electrical:*

The following design tests shall be made in enough complete insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the performance of the type. The insulator shall stand without failure:

A *dry arc-over* test of not less than three times potential between line wires applied for one minute.

A *wet arc-over* test of $2\frac{1}{4}$ times the potential between line wires for one minute.

SUSPENSION TYPE INSULATORS

24. *Inspection:*

All parts shall be inspected before assembling.

25. *Electrical Tests Before Assembling:*

The unassembled porcelain disks shall be given a regular routine electrical test at a voltage 10 per cent below flash-over potential for five minutes. If puncture occurs in the fifth minute, the tests must be continued until no puncture occurs in one full minute of test.

26. *Mechanical Test:*

After approximately ten days setting of the cement, all units shall be given the regular routine mechanical test of ..... lb. (..... kg.), with tension applied in line with the axis of the insulator.

27. *Final Electrical Tests:*

All disks shall be tested at a voltage 10 per cent less than flash-over for two minutes. If puncture occurs during the last minute the test must be continued until no puncture occurs in one full minute of test. This test shall be made after the mechanical test above prescribed, §26.

28. *Design Tests—Electrical:*

The following design tests shall be made on enough complete assembled insulators, not exceeding $\frac{1}{4}$ of one per cent, to determine the performance of the type. The insulator shall stand without failure.

A *dry arc-over* test of the complete insulator, consisting of ..... units, of ..... volts, applied for one minute.

A *wet arc-over* test of each insulator, of ..... volts.

It is preferable that the arc-over of the complete insulator shall be over the insulator as a whole and shall not be over the individual elements.

There is no advantage in a dry flash-over strength greatly exceeding the wet flash-over strength and there is the disadvantage of the greater danger of puncture. The wet flash-over voltage should not be less than twice the voltage between line wires.

29. *Design Tests—Mechanical:*

At the option of the purchaser or his engineer, one-tenth of one per cent of the whole number of assembled parts forming one element may be mechanically tested to destruction. Where practicable such units as are rejected for other causes shall be used in making this test.

APPENDIX

The following tests are recommended as desirable where appropriate. They are not incorporated in the above tests as experience with them is not yet sufficiently broad.

30. *Uniformity Test:*

Twenty-two single disks or elements taken at random from stock which have passed factory test, shall each in turn be placed in oil, potential not exceeding 30 to 40 per cent of arc-over voltage shall be applied, and gradually increased at about the rate of 1000 volts per second until puncture shall occur. Any twenty of these values of puncture voltage shall then be selected by the maker. The difference between the maximum and minimum puncture voltage must not be more than 20 per cent of the average voltage. This test should be repeated with one or more additional groups of 22 disks, not exceeding in the aggregate ¼ of one per cent of the total, enough to determine the uniformity of the product.

31. *Impulse Test:*

Twenty-two units shall be selected at random. Each of these disks, or preferably several disks in series, shall be connected in turn to the impulse circuit shown in Fig. 1, p. 1460. The gap *A* shall be set at three or preferably four times the arc-over voltage of a single unit. The voltage shall be increased until gap *A* arcs over, when the circuit shall be immediately opened by breaker. This

shall comprise a "stroke." ..... strokes shall be applied to each unit or string of units or until puncture occurs. Preference shall be given to the insulator showing the greatest uniformity and the highest average puncture voltage. Referring to Fig. 1, page 1460, the shunt condenser capacity shall be..... microfarads, and the inductance ..... millihenrys.

NOTE: The above test will show, in a general way, the probable effect of surges, lightning, etc., on the life of the insulator, as well as uniformity of the porcelain. The number of strokes, and voltage, to puncture, will depend upon wave front of impulse, or frequency, etc. This cannot now be definitely specified, as the phenomena have not yet been sufficiently investigated. A test as above, however, is very important in competitive tests.

32. *Rain Tests—Position of Insulator:*

With pin insulators, where more convenient, instead of inclining the spray at 45 deg. with the insulator, the latter being vertical,—the spray may be made vertical and the insulator inclined at 45 deg.

DISCUSSION ON "SUGGESTED SPECIFICATIONS FOR TESTING HIGH-VOLTAGE INSULATORS" (PEEK, SANDFORD AND THOMAS), COOPERSTOWN, NEW YORK, JUNE 25, 1913.

F. W. Peek, Jr.: The line insulator is an important factor in determining the success or failure of a transmission scheme. The requirements in present insulator specifications in no way provide for uniform porcelain. Destructive puncture tests are generally made on a few selected units which may indicate a very good insulator. On account of the great lack of uniformity in most porcelain these tests do not determine the performance of the bulk of the insulators which are manufactured later and put on the line. It is thus seen that uniformity of the porcelain is one of the most desirable features of a line insulator. I should like to bring out a few points that should be covered. In almost all other engineering work the strength of a given material is known and can be depended upon within a small per cent of the value indicated by test pieces. The material is uniform, and uniformity is a necessity. If structural steel varied a tenth as much as most porcelain used in present line insulators, there could be no "sky scrapers." Tests, then, should be such as to secure uniform porcelain. This might be accomplished by requiring the destructive uniformity test, or the impulse test, made on insulators taken at random from different parts of the kiln at each firing. Again, the specifications might require that a certain percentage of the insulators of each kiln at each firing pass the factory test, otherwise *all the insulators of the kiln* at the given firing be condemned. For instance—if in one firing in a given kiln 50 per cent of the insulators fail to pass the factory test, and if in the next firing only 10 per cent fail to pass the factory test, the insulators in firing No. 2 would be much more reliable. A greater percentage would stand voltage rises on the line.

I do not believe that the factory tests made on all of the insulators should be too severe. For example, an exceedingly high voltage of steep wave front, or short duration, may be impressed upon an insulator without any apparent damage, but nevertheless the insulator is weakened. It may be that after nine of such applications there is no visible change but on the tenth application puncture may occur.

This is probably one reason why insulators that have long given good service after a time begin to break down, by the weakening due to accumulative effect of impulses received in service caused by arcing grounds, arcing over of poor insulators, lighting, etc.

It is desirable to make such tests, but only on insulators that are not to be used on the line. These tests indicate what can be expected of the bulk of the insulators if the porcelain is uniform.

Some suspension insulators recently came to my attention which had passed factory inspection. These would ordinarily have been placed in service. On breaking a few it was seen

that the porcelain was very porous. Such insulators puncture at very low voltage when dry, and when the glaze becomes checked, breakdown will generally occur in practise. Moisture is undesirable in the cement even when the porcelain is good. Cases have come to my attention where, due to the cement and moisture, the metal pin was chemically affected. A coating formed on the pin. The pin, thus increased in size, placed the porcelain under great mechanical stress, probably producing tiny cracks. When puncture occurred in such insulators due to lightning, even when dynamic was not on the line, the cap was ruptured as in a boiler explosion, dropping the line to the ground. The explosion was probably caused by sudden expansion of moisture in the cement. The mechanical stress and tiny cracks therefrom weakened the insulator so that puncture also took place at line voltage. Moisture-proof cement seems desirable.

It is very important that when arc-over occurs, the design should be such that it takes place completely around the string and not from unit to unit in cascade. Complete arc-over is most likely to be obtained if the voltage balance of the string is good. When arc-over takes place in cascade the equivalent of successive impulse tests are played on the units as the arc approaches the tower unit, until finally, when the tower unit is reached, the full line voltage or over will be on this unit until it arcs over or punctures. A cascade arc also heats the units more than a complete arc, and breakage due to heat, and hence dropping of the line, is likely to occur.

It is not often realized that altitude makes a vast difference in arc-over voltage of insulators.

In making insulator tests, the transformer ratio should be calibrated with the sphere gap to include wave shape. Voltage may then be measured by ratio if the same method of voltage control is used.

In all engineering work the cost of various factors must be so divided that a maximum return is obtained from the investment. Engineers should realize that it is better to pay more at the start for a good and wisely selected insulator than to pay many times later by the loss of prestige due to poor service, and by damaged apparatus, to say nothing of the replacement of insulators. Each insulator that punctures or arcs over sends out impulses of high frequency which may weaken or destroy other insulators and apparatus.

While good uniform porcelain is necessary, it must be remembered that good porcelain does not always mean a good insulator, that good insulators may be weakened by improperly adding perfectly good porcelain.

My "Suggested Specifications" do not require an ideal insulator, but are requirements which I believe can be met at the present time by any manufacturer at reasonable cost. The suggestions are given not so much to make fixed specifications,

but rather to bring out points not often realized. It is to be hoped that it will not be long before insulators are designed with due regard to the dielectric circuit, and that porcelain is either superseded or becomes a uniform dependable product.

J. A. Sandford, Jr.: In looking over these specifications with the criticisms, from the insulator manufacturers' standpoint, I would like to have you look at them as much as possible from the standpoint of specifications written to cover the requirements which are necessary in order to produce a good quality of insulator, and not so much a specification to cover the design of the insulator which the purchaser may choose. Undoubtedly, a set of specifications which the purchasing engineer writes must include paragraphs covering certain points that will govern the design, or performance tests, you might say, of the insulator completely made up.

It would seem to me as though, if it were possible to do so, it would be well if all specifications for tests that are required to demonstrate the performance of an insulator could be written up and isolated from the tests that are required to demonstrate the quality of the porcelain in the insulator to show that good insulators are being shipped. The reason I say that is this: After the insulator has been decided upon and the contract has been signed, the greatest thing that has to be contended with, very often, is the judgment of the man sent to the factory to select the individual units for insulators out of the lot put before him. For this reason it is advisable to have as few points as possible left to be decided by the inspector. If the purchaser's engineer decides all points concerning design, it will only be necessary for the inspector to see that good material is furnished; that it is according to drawing, and that the proper tests are applied to all units. It seems to me it would be more satisfactory and to the advantage of all concerned if these things could be separated, but that is hardly possible. At the same time, from the factory standpoint, that is the way the specification should be looked at; *i. e.*, simply from the standpoint of producing good insulators of the design already contracted for.

Referring to the paragraph headed "Corona" in Mr. Peek's specifications, I believe I am perfectly safe in saying that there is not a single type of suspension insulator on the market to-day that would not show corona around the metal stud cemented into the under side of the unit, if tested at 1.3 line voltage, assuming this to be 110,000 and the number of units per insulator as seven. I am pretty sure that there are a good many 110,000-volt insulators in use to-day that will show corona at about 65,000 volts. To be sure, it is very slight, but at the same time it is visible, and there again comes up the question of judgment of the man who has these things to decide, as to how much he is going to allow. If you leave the wording in the specification so that it will read "there must be absolutely no sign of corona," prospective purchasers must buy a different

insulator from that which has been used for like conditions in the past with seemingly satisfactory results.

Referring to the pin type of insulators, there is one thing which might have been added which would have read something like this: "In no case is any porcelain part to be tested at less than 70,000 volts." As a matter of fact, we never test any porcelain part ourselves at less than the voltage that the part is designed to stand when assembled as a part of a complete insulator, and we think that is a safe practise.

Now referring further to the pin type specifications, mechanical test, that is stated as a definite figure at 2000 lb. I think that this value would apply all right in all cases for insulators of 25,000 volts or higher. I think possibly, however, that this value should have been left blank, because in the case of some of the smaller insulators, say 10,000 volts, or 11,000 volts, it might be found possible on some designs to approach that figure, but it is my experience in 90 per cent of the cases where we are called upon to apply a certain specification test to the pin type insulator as indicated, that the test usually resolves itself down into a test of the pin, because the pins generally bend at a considerably less load than 2000 lb., and particularly on a 60,000-volt insulator of the largest size.

Referring to the paragraphs headed "Minimum Distance from Insulator to Grounded Objects," and "Number of Insulators to be Tested at One Time," and "Factor of Safety—Dry," etc.; when Mr. Thomas received the first draft of the specifications I submitted to him, he asked me several questions, and these paragraphs might be considered as answers to those questions. In other words, they are the view that the porcelain manufacturers take of these subjects, particularly from the point of producing good quality insulators, not that some of these points might and ought to be included in the performance test, preliminary to the placing of the contract.

Under the heading of "Quality of Water for Rain Test Purposes," the first time I encountered this difficulty was when we were put to it to make a certain suspension type insulator come up to certain requirements under the rain test, and I could not do it with the equipment I had, using everything as it was installed. We had our water from artesian wells, water coming up through several layers of gas beds, coal fields, etc., so in order to take up the problem and solve it we took the identical insulator disks tested in our own factory, the spraying outfit and everything that was movable, and transported them to Pittsfield, Mass., and we made another test there. The results were rather startling. We then took the specific resistance of the water; the first (Lisbon) water was 880 ohms, and the second (Pittsfield) water was 7000 ohms. Later we installed in our factory for this kind of work a little half-inch steam trap and tank to collect water from our heater system, and let the water cool down and used this water for similar testing

purposes. The specific resistance of this water was 30,000 ohms. I have the apparatus so arranged that I can turn one valve for one water and another valve for the other water, and the difference will run as high as 40 per cent.

I think the specification that has been written by Mr. Thomas, with those points left blank, so far as the actual value is concerned, is a good one, and as I stated here, in my report, this method of obtaining a good water may be put in practise. I think this apparatus could very likely be installed at any place where the test was likely to be made.

Referring to the dew test, from our standpoint it does not show anything in the performance of the insulator over what can be obtained in other ways. In the winter time I believe we can get a better test than any dew test would be by simply hanging the insulators out of doors and bringing them indoors and applying the test immediately. In this way you get a coating of moisture over the insulator which is better than that put on by steam or any other method.

The question of the capacity of the equipment is a thing which seems to be more or less a bone of contention. It is oftentimes specified, but often winds up, and probably has to wind up, by the engineer accepting what he finds at the manufacturer's plant at which it seems most advantageous to him to place his order. I think in nearly every case all the insulator manufacturers have a good equipment, and it seems to me that so far as any routine factory tests are concerned, that it need not be thought of in the specification. If there are any special performance tests where very careful note is to be taken of small variations in the performance of the insulator, then it is well to specify the various conditions, and among others the capacity of the equipment; but generally tests of that kind are made in a laboratory which has at its disposal various capacities of equipment and therefore such specifications may be admissible.

Now the method of controlling the voltage is subject to about the same limitations; that is, the potentiometer method, I believe, is good, but you realize the manufacturer is cutting down his costs just as far as he can for the factory tests and the potentiometer method of making the test will be very expensive. Take for instance a porcelain plant. Either one of our plants is probably as large as any other one plant in the business, and even at that we only require about an average of 80 h.p. to drive the whole factory. If you are going to load up a considerable per cent of that by using up power in water resistance, the people who are paying the bills will object, and I can see no reason why that should be necessary, except, again, in cases where performance tests are being made and a careful note has to be made of small differences, in which case it looks to me like a laboratory proposition and should be so treated.

You can see I am looking at this purely from the standpoint

of the quality of the porcelain; therefore the grounding of one end or the middle of the test circuit goes along the same line except that for convenience it is very much easier for us to use the middle point grounded, on account of the fact that we have only to insulate through the buildings at half potential. We were compelled to put up sprinkler systems everywhere, and the less voltage we have to insulate in the factory the better off we are.

In regard to the paragraph concerning the breakdown of the insulator. Generally the breaking down of an insulator means the total destruction of that insulator, and if it would be consistent, I think it would be well to have that so understood.

The corona discharge, etc., is often specified, and with reference to what Mr. Peek says, that there shall be "absolutely no corona," if we make a performance test at our factory, or at some other factory, or at some neutral point, and along comes an inspector and we make another test, and in his judgment the above specification is not fulfilled, what is going to be the answer? It seems to me the items I have taken up in that last paragraph on page 1469 and the paragraph at the top of page 1470 should be wholly and finally decided before the contract is signed and then remain as decided, because you cannot change the insulator afterwards. I have seen strings of insulators sometimes, among which, right along in the same string, there will be one unit absolutely dark between two units that show considerable corona.

As to the test for the puncture strength of the insulator, such test to be made under oil, I think this test is a very good thing. I cannot quite agree with Mr. Thomas, however, as to the method of raising the voltage by a thousand volts a minute, or whatever other time might be adopted, because ordinarily the factory equipment at an insulator factory is not calibrated, the low-voltage meters which they have are not calibrated so that they read directly in kilovolts on the high-tension side. I rather like the method which I suggest here in the last part of this section. I used the old method myself at one time, but since then I have had a considerable amount of experience in applying the voltage in this way and I may say it works out very well indeed and will show up results as well as or better than any other method I ever tried for testing under oil.

As to the last paragraph, there is not anything better that I know of that can be said on that than to look at Mr. Nicholson's paper for this part of the discussion. First of all it is a design test, and it is difficult to apply because ordinarily the mechanical testing equipment in the factory may or may not be anywhere near the electrical equipment, and it means there must be provided special arrangements, etc., for rigging it up. But there are one or two things which Mr. Nicholson says here, which, if they are substantiated by more tests later, it would seem to me would justify by good proof our taking the stand that I have indicated in this last paragraph, viz., in eliminating such a test,

because you will see in Mr. Nicholson's discussion that he says: "In our effort to explain these results, mechanical loads were applied to insulator disks and then removed, voltage being applied after the removal of the loads. In other words, the electrical test followed the mechanical test. Almost identical results were obtained by this method as in the simultaneous electrical and mechanical tests. This fact seems to indicate that puncture occurs by reason of injury to the porcelain by the mechanical load, rather than by a combination of mechanical and electrical stresses acting simultaneously." If that proved true, in more extended experiments—we have not done much on it ourselves—I see no reason why then we should not apply a routine test to all units, which we do now. We may have to raise that a little and then apply our flash-over test with a definite time-limit rather than an instantaneous test, I think, and accomplish just as good results; in fact better, I believe, than by trying to determine the result from using the simultaneous test.

Further on Mr. Nicholson says, "Moreover, it is noteworthy that usually an insulator during or after a mechanical load which caused puncture, would withstand flash-over voltage for several seconds' time before puncture occurred. These observations indicate that mechanical loads insufficient to actually crack the porcelain may overstrain it to a point where its dielectric strength is greatly reduced." I do not know, but I think that if all the insulators that were put to that test were of uniform vitrification, this difference would not exist; in other words, if the insulator was damaged at all, it was punctured practically instantaneously with the final voltage. It seems to me if that condition is going to exist, the thing I spoke of a short time ago should be introduced and I have written this down as an addition to that statement: "If this condition is found to prevail after more numerous data have shown such to be the case, the final electrical tests after the mechanical pull should be for a definite length of time, not for the so-called 'instantaneous' application."

I think if that condition exists, a test, perhaps one of two minutes, or whatever may be thought to be a proper time element, would weed out any such cases.

What we would like to see would be a set of specifications drawn up that will not put any more fussy testing and experimental work than necessary up to the manufacturer after the contract is signed. It seems to me all these things should be determined beforehand and that afterwards all there is to be done is to be sure that each and every insulator and each and every piece of porcelain of a completed insulator, in the case of the pin type insulator, is perfect or as nearly perfect as we can make it. It makes it easier for the inspector, the manufacturer and the purchaser, and the purchaser will get just as good material in the end.

P. H. Thomas: I will take a few minutes to call attention to certain parts of the third specification, the one drawn up to

embody what seemed to be the best and most practical features of the specifications which you have just heard discussed.

On page 1472, section 6, I have suggested a factor of safety for testing on metal parts. I do not believe such a requirement has been usually made, and I do not suppose it is necessary to put very much stress upon it, but it gives a criterion for the guidance of the man who is designing the mechanical parts.

On page 1473, paragraph 9, reference is made to the absorption of moisture by the porcelain. This is taken from Mr. Peek's specification, and is, I think, a very important feature. Personally I am inclined to believe that the amount of absorption is a very good measure of the density and quality of the porcelain. I would call the attention particularly of the manufacturers to the question as to whether they feel that this value given in paragraph 9 can be reasonably and reliably attained. Mr. Peek gives an absorption of not more than 0.25 per cent, and Mr. Sandford, in his case, gives 0.1 of 1 per cent, with a differently worded method of making the test. I have put in Mr. Sandford's figures in the specification, and ask that this point be discussed. One-tenth of 1 per cent may be too severe a requirement.

At the bottom of the page you will notice that I have made a careful distinction between routine tests and design tests. This is in line with the request of Mr. Sandford that when we have once decided on the design then it remains to make tests on individual units which shall insure that the insulators reasonably correspond to these designs. All that is required for the routine tests is that once in a while the method used for the routine test be calibrated by the prescribed method of making tests, and any reasonable method of checking up the voltage as shown on the test can be used. That gives the manufacturers an opportunity of using any apparatus which they may have available, provided it is reasonably good, for handling their factory output.

Paragraph 16, with relation to frequency, is a compromise. Ideally, we should test every insulator on the frequency at which it is to be operated, but it is a hardship on the manufacturers to require testing at the various commercial frequencies. I am inclined to think that in ordinary cases a 60-cycle test would show pretty nearly the same results as 100-cycle or 125-cycle test, up to 40,000 volts, provided the other conditions were as specified. The variations between frequencies in testing are due to many other things than differences in frequency, such as differences in the characteristics of transformers, the characteristics of the generators and the methods of the application of a voltage.

The next paragraph, on "what constitutes a breakdown," is perhaps the first definite injection of such matter into a specification. This paragraph comes from Mr. Sandford's specification.

The oil tests, it seems to me, are absolutely necessary in important lines. How large a percentage over the flash-over voltage shall be required for the test under oil for the puncture

test is open to debate. It is given as 125 per cent in this specification.

As to paragraph 22, in reference to mechanical tests on pin insulators. I would like to read the last sentence. This is a novel statement, and whether it will be approved or not I do not know. It is as follows: "In case of failure the question as to whether the insulator or the pin is at fault shall be determined by testing again with a solid steel pin turned from a piece of round steel of such dimensions that this piece of steel acting as a pin for the insulator will not bend under the above-mentioned load." In my opinion it is not sufficient to put in a perfectly good pin to find whether the insulator will stand the overload, but the pin which is used should be one which will not bend or spring in service, so it seems to me worth while to make the test on the design with the pin you are going to use.

Paragraph 25, and other paragraphs in this group, refer to routine testing. The question is as to how long these tests shall be continued, and that is one of very considerable practical importance. When you are making a test of one thousand insulators, it makes a difference whether every one must be tested one minute or five minutes.

I would call on Mr. Nicholson to read the contribution which he has made, which contribution has been printed, and which describes some of his tests on a simultaneous application of electrical and mechanical stresses. I consider this a very important matter, and I would like to have it called to your attention at this particular point in the consideration of these specifications.

L. C. Nicholson: A series of tests, not yet completed, has been undertaken to determine the performance of suspension type insulators when subjected simultaneously to electrical and mechanical stress.

We find that mechanical loads do not affect the flash-over value of the insulators, but do affect the puncture or dielectric strength. A load much less than that necessary to cause apparent mechanical failure induces puncture at dry flash-over voltage. Thus, insulators having an ultimate mechanical value of 9000 to 12,000 lb. (4080 to 5440 kg.) will puncture when subjected to from 4000 to 9000 lb. (1815 to 4080 kg.) pull and dry flash-over voltage simultaneously.

Mechanical load was applied by means of an overhead hand crane, three insulator disks in series being anchored to floor. Voltage was obtained from a 50-kw., 25-cycle, 250,000-volt testing transformer, regulation being effected by a water rheostat.

Expressed in per cent of the number of disks tested under ascending mechanical loads we find that:

5	per	cent	puncture	at			4000 lb.	(1815 kg.)	pull.
8	"	"	"	"	or	below	5000 lb.	(2270 kg.)	pull.
22	"	"	"	"	"	"	6000 lb.	(2720 kg.)	pull.
50	"	"	"	"	"	"	7000 lb.	(3175 kg.)	"
90	"	"	"	"	"	"	8000 lb.	(3630 kg.)	"
100	"	"	"	"	"	"	9000 lb.	(4080 kg.)	"

Several types of insulators from several different manufacturers were experimented with. No marked difference between the different kinds was found to exist, with perhaps one exception. This was a "strain type" insulator with extra heavy metal parts. Only a few of these were available, but none of those tested punctured at a load of less than 8000 lb. (3630 kg.), and some of them withstood 10,000 lb. (4540 kg.) successfully. The ultimate strength of this insulator was from 10,000 to 12,000 lb. (4540 to 5440 kg.).

In our effort to explain these results, mechanical loads were applied to insulator disks and then removed, voltage being applied after the removal of the loads. In other words, the electrical test followed the mechanical test. Almost identical results were obtained by this method as in the simultaneous electrical and mechanical tests. This fact seems to indicate that puncture occurs by reason of injury to the porcelain by the mechanical load, rather than by a combination of mechanical and electrical stresses acting simultaneously.

Usually, though not always, puncture occurred previous to any audible noise from the insulator, such as would indicate crushing or cracking of the porcelain. Moreover, it is noteworthy that usually an insulator during or after a mechanical load which caused puncture would withstand flash-over voltage for several seconds' time before puncture occurred. These observations indicate that mechanical loads insufficient to actually crack the porcelain may overstrain it to a point where its dielectric strength is greatly reduced.

We believe the shape of metal parts, as well as the size, shape and distribution of grooves in the porcelain, are important factors in this matter. Undoubtedly other factors and effects are present, and the subject is one deserving careful study and investigation.

As to the theory of what happens I am not able to say. I have simply pointed out in my discussion the results which are obtained.

There is not much audible noise. In many cases the insulator will hold the voltage for 30 seconds before it punctures, indicating that the material may have been strained, although not actually cracked. This factor varies with different shapes of hardware and different shapes of porcelain, depth of grooves, distribution of grooves and all that sort of thing. I have not begun to find out the nature or extent of the phenomenon.

P. H. Thomas: You can see this work of Mr. Nicholson was a serious matter. There are in service a great many strain insulators of the type tested, and much difficulty is experienced with them in the respect indicated. Our specifications ought to protect us against it. At the present time we do not have data enough to conclude just the significance of this feature which Mr. Nicholson points out. It may be that further experiments will show that the weakening of the dielectric by mechanical stress is an extremely common occurrence.

We are especially interested in what the cause of the trouble is and what is the nature of the action. It is a speculation at the present time, but the thought must occur to us that there is a mechanical deformation of the parts which are under a strain approximating the elastic limit. We have metal parts, porcelain parts, and cement parts, and under the strain there must be a certain amount of mechanical change of shape. Porcelain is a brittle substance and it is possible there are tension strains developed in it which will cause not a clear crack, but an opening up of the material which allows a little penetration of charge. This speculation is supported by one of the comments of Mr. Nicholson that there was one set of disks which did not act as badly as the others and that this set had excessively heavy mechanical parts. If it is true that distortion is the cause of the difficulty, it can be corrected.

I think we have done all we can in these specifications to forestall the effect of mechanical stress in calling for the making of the electrical routine test after the mechanical test. Mr. Nicholson's study as far as it goes, shows the test is no more severe made at the time of the mechanical test than it is afterwards.

I hope that all engineers interested will make full criticism of these proposed specifications.

H. W. Crozier: What has become of the idea that each unit in a string of insulators should be able to stand the line potential? That idea was advanced some time ago, that is, that each unit should be able to stand, as a puncture test, the line voltage.

I want to add a word of caution in regard to the mechanical tests proposed. Mr. Nicholson's discussion particularly brings this out. In a good deal of work which we did, samples of the insulators were tested to destruction. In our practical insulator work we are not testing samples, but we are testing actual insulators, and we must take care we do not do things to the insulator in our testing which will reduce their efficiency. We may take strain insulators capable of standing 15,000 lb., and we can easily realize from Mr. Nicholson's discussion that if we overload these insulators we greatly reduce their resistance to electrical puncture. If we take all the insulators of a line and apply a severe mechanical test to them, we have reduced the resistance to puncture of the whole number of insulators by a margin of forty or fifty per cent. We will have to test a lot of insulators mechanically to provide for strain insulators, but for the other insulators, which are going to act as supporting insulators and throughout their life may not be called upon to support more than a few hundred pounds, it would be desirable to omit the mechanical test altogether.

P. H. Thomas: Has Mr. Peek, or Mr. Sandford, anything to say about making each unit in the string stand the line potential? That would seem obviously impracticable when you have high voltages. It might be practicable in some cases, but if you have seven or eight insulators in a string, it would be impracticable, in my opinion.

J. A. Sandford, Jr.: If Mr. Crozier adds under oil, there is no insulator made today that will not stand the line potential under oil.

H. Koganei: With regard to the oil test of insulators, I made a series of tests and observed some phenomena which are not yet well explained. The insulators tested were all of pin type for working voltages of 15,000, 25,000 and 35,000 volts. At first I made the arc-over test with three times working voltages for five minutes. Then selecting ten insulators from each size which arced over without puncturing, I immersed them in oil to make the puncture tests. The puncture voltages varied from 80 to 90 per cent of the arc-over voltages.

It seems quite reasonable to show lower puncture voltage in oil due to the concentration of the dielectric field near the terminals. To eliminate this effect of the field distribution, I selected another lot of ten insulators from each size and pasted tin foil on the top and the pin hole. Even in this case they were all punctured at the same voltages near the center of the electrodes and none at the edges.

The voltage was measured by the needle gap, which checked very well with the voltage calculated from the turn ratio. The voltage was increased at the rate of 1000 volts per minute.

The flux distribution in the latter case, near the puncturing point, may be considered to be more uniform than in the arc-over test. Nevertheless, the insulators were punctured in the oil at least 10 to 20 per cent lower voltage than they will puncture in the air. Unfortunately, these tests were made just before I started from Japan and I did not have enough time to get any further result. The insulators were made in Japan.

F. W. Peek, Jr.: The suspension insulator as a rule does not act in that way under oil. The only explanation would be some local concentration of flux due to the oil, and with the suspension type, the breakdown under oil always takes place between pin and cap where the oil can in no appreciable way affect the flux distribution. The flux distribution would be affected in the pin type insulator. I do not think the oil has any peculiar effect.

M. T. Crawford: Mr. Sandford recommends the wet flash-over voltage test for pin type insulators to be not less than 175 per cent of the operating voltage. My experience has been that not less than 200 per cent normal voltage is a better minimum, or possibly 225 per cent as recommended by Mr. Peek. I have also found it to advantage to have each insulator marked with an identifying stamp by the inspector, so that none are skipped in the test by mistake during a rush delivery. On one job of over 30,000 insulators tested in this way to over 200 per cent normal voltage. There have been practically no failures in four years' service, whereas another job with a less rigid test has given a considerable number of failures, although they have identically the same design and are used under the

same operating conditions. In this case the greater cost of the insulators tested with the higher pressure was more than warranted.

P. H. Thomas: In regard to the propriety of omitting the mechanical test on insulators which are not to be used as strain insulators, something may be said both ways. In the third specification, paragraph 22, page 1476, a blank is left for the value of the pull test. If it is desired, insulators can be made in two classes, one to receive a test commensurate with the ordinary strain of the line insulator, and the other for the high strain of the strain insulators; since by the breaking of a conductor a high mechanical strain is likely to be brought on a suspension insulator, it seems to me it would be, as a matter of fact, and of practical wisdom, dangerous to try to use a suspension insulator that would not stand the strain of a broken conductor.

J. A. Sandford, Jr.: It seems to me the strain insulator is the one to stand the load. If there is any damage done by applying the mechanical stress, that is the one to receive the stress, and it should not be received by the span insulators.

L. C. Nicholson: Insulators intended for service should not be damaged by mechanical or other tests, but it is evidently unwise to place an insulator in service subject to a certain mechanical load which has not been actually tested somewhat in excess of the loading it will receive under actual operating conditions. If there is any question as to the ability of the insulator to carry this load, two or more insulator strings should be used in parallel.

There has been considerable trouble with strain insulators on transmission lines. This has been attributed by some to too high mechanical loading, and by others to the self-induction or choke coil effect of the conductor loop as usually employed at angle or dead-end towers. No one seems to have any definite explanation of what is responsible for strain insulator trouble. The mechanical-electrical tests cited show that dead-end insulators may be weakened electrically by mechanical loading. Furthermore, these tests were of short duration, and do not tell us what effect would come from alternate loading and unloading over long periods of time such as occur in practise.

In addition to mechanical loads, internal stresses of considerable magnitude are induced by atmospheric temperature changes. In a paper by Mr. Austin before the National Electric Light Association, at Chicago, it was shown that a stress of at least 400 lb. per sq. in. may be induced. Since this value is practically one-half the ultimate strength of the porcelain, it appears that medium mechanical loading in combination with temperature effects may in time result disastrously to the insulator.

These considerations indicate that the shape of suspension insulators may be changed to advantage—better to withstand loads and temperature changes. Are we not making an error

in the construction of the insulator in confining a small knob of porcelain in a perfectly rigid iron pocket? Or, would not some substance other than cement, which would be more elastic, be better in this respect?

In general, the points mentioned in the specifications under discussion are good, but I believe they do not go far enough. There are a number of important things about insulators which we do not know, and which we appear perfectly content to leave to the manufacturers, without making an effort to find out about them. The manufacturers are in general reliable and honest, but have not so far sufficiently distinguished the technique of insulator design from the commercial production of insulators. Electrical engineers are willing to leave these matters entirely in the hands of the manufacturer, and depend upon final test and inspection to secure satisfactory insulators. For example, we never ask any questions nor make any requirements relating to the composition of insulators we intend to use. We leave the entire ceramics of the matter absolutely in others' hands, and have made no efforts to study intelligently the composition or firing of the porcelain. In a matter so important to the electrical industry, I feel that the American Institute of Electrical Engineers or some other body should undertake to become familiar with insulator production, to the extent that specifications may be prepared covering not only the testing, but the composition and production of insulators.

The point raised by Mr. Peek concerning proper spacing of units to prevent flash-over in cascade, is in my experience of slight practical importance. With the usual spacing of units, when dry the string flashes over, but when wet the units flash over individually. Since the wet condition is the practical one, I fail to see any advantage to be derived from a close application of the theory based on dry flash-over.

C. O. Mailloux: I would like to say a few words about going into the mixing room too early. I have had some experience in cases where it was necessary for the consulting engineer to decide whether there was to be or was not to be a mixing room. I have found it to be true in electrical engineering, and in all other professions, that the shoemaker should stick to his last. I think it is dangerous for the electrical engineer who has not made a thorough study of ceramics, at least as thorough as the ceramic expert himself, to go into the mixing room and tell the ceramic manufacturer what to do. There is a parallel case in the manufacture of insulation for wires. I have found that in undertaking to tell the manufacturer of insulation for wire, how to manufacture and how to apply the insulation, one was liable to hamper the operation most seriously and make difficulties which not only tended to, and actually did, increase the cost of the output, but also decreased its insulating and lasting qualities. Hence, in my opinion, it is quite as well to

let the ceramic expert confine himself to that specialty. I do not care how strongly we insist on the *results*, but when it comes to the methods of accomplishing these results, I think we should leave to the manufacturer the widest possible latitude.

Paul M. Lincoln: Concerning the quality of water which is recommended for making the rain test, I have run across a good many different kinds of water, and I find there is a tremendous variation so far as their electrical resistance goes. Some water is a fairly good conductor and some is a pretty good insulator. It seems to me Mr. Sandford is quite logical in suggesting in his specifications that the water which is used for rain tests in testing insulators shall be condensed steam, for the reason that the water which wets the insulator in practise is of the same nature, viz: rain-water, and it is practically pure. The only opportunity it has for gathering up impurities is in the course of its descent through the air, and while it may take up a very small percentage of impurity from the air I do not believe that is sufficient to make its character very different from that of the condensed steam which Mr. Sandford suggests.

Another point is one in which I cannot agree with Mr. Sandford. He suggests that the connection of the transformer which shall be used for testing—whether it be grounded in the middle or at one end—shall be at the manufacturer's convenience. I know from my own experience that there is a tremendous difference between these two methods of connection. It is on account of the disposition of the static field around the insulators.

Insulators, when used, have the pins grounded, and I believe the test should be made under the same conditions, as nearly as possible, and I therefore believe the specification for testing insulators should carry with it the condition that the pin of the insulator shall be grounded during the test.

Percy H. Thomas: We meet both conditions in some specifications. The design test is made on the nearest approximation test to the service conditions, and for the routine factory output the test conforms to the calibration of the low-voltage voltmeter, with the result that we approximate the actual conditions, and make the output test with the easier apparatus.

A Member: I would add a little to what Mr. Mailloux said about the danger of going into the mixing room, and I will refer to some experiences I was familiar with, in which one body of engineers, in making a report, stated that they had told the manufacturer not only what to put in the mixture for the insulation, but how to put the insulation on the wire also.

In any consideration of the subject of the composition of mixtures of any kind, and their application, we must realize that improvements are being made all the time and that any specific directions which an electrical engineer might give on this subject would not hold for very long.

Hugh T. Wreaks: Referring to the point brought out by Mr. Sandford about the question of packing, this seems to me very important. In specifications of many other kinds of material, specific attention is given to how the material should be packed. We have had occasion to note damage in shipment of insulators, and even in cases where the penalty for breakage came on the manufacturer, a good many were damaged in shipment.

Judging from experiments of Mr. Nicholson, it seems to me not unlikely that many insulators may be strained in shipment, with consequent weakness developing in the field, the fault in this case being due, not to how insulators were manufactured, but to how they were packed and handled in shipment.

E. E. F. Creighton: The endeavor to standardize the tests on insulators is, I think, a valuable move in the right direction. Even if the rules are not adopted, they will have their value. Although it is impossible to get any information at the present time on the proper manufacture of porcelain and therefore it cannot be included in these rules, yet this is one of the most important features regarding the insulators. Sooner or later some one must make a careful investigation, for the information of electrical engineers, of the following factors:

First. The effects of each of the ingredients that go into porcelain.

Second. The proper deposition and drying of this material without allowing flaws to be formed in the body of the material.

Third. The proper temperature and proper length of time of firing for proper vitrification.

There is little practical use in stating that porcelain should be properly vitrified unless some specific directions can be given. The absorption of water by porcelain has been used as a rough test of the degree of vitrification but the method is unsatisfactory in several respects, especially in the fact that it requires the destruction of an insulator. From the experiments I have made I think it is possible to develop some other method which will be not only more satisfactory but will leave the insulator intact after testing.

Along a different line of endeavor some experiments made on clays relating to vitrification, are apropos to the problems of porcelain manufacture.

Our tests were made on the vitrification of clays, using as a basis of vitrification the stability of the material as a resistance; at 1200 degrees there was very little vitrification; at 1300 degrees vitrification was fairly started; and at 1350 degrees complete vitrification took place, although as high a temperature as 1500 degrees was used at times to advantage, for the particular work in hand.

Another test made in vitrification was relative to the time of heating. The material was heated successively for periods of about one-half hour and measurements were taken after each heating. The curve showing the general relations is given in the accompany-

ing Fig. 1. The degree of vitrification is represented by the conductivity. In the curve the reciprocal of conductivity, namely resistance, is given. These curves of time versus vitrification vary in form according to the temperature used. Naturally, the higher the temperature, the more rapid the vitrification.

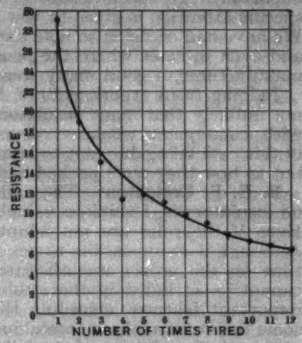


FIG. 1

This curve shows the relative degree of vitrification of clay by the decrease in ohmic resistance. The duration of each firing was approximately one-half hour. The last few tests showed almost constant resistance, which we presume indicates the final condition of vitrification for the particular temperature used, namely, about 1400 deg. cent.

Although these tests were not made directly on porcelain for insulating purposes, it seems that they would show the necessity of scientific work being done in the manufacture of porcelain. Until this work is done results will vary tremendously.

In all other forms of insulation the manufacturer aims never to test the insulation to anywhere near its complete dielectric strength. Destructive tests are made on samples of material, and the methods of manufacture are regulated to keep the product uniform. With the methods of manufacture fixed, a factor of safety is taken on the dielectric strength of this material and is then not strained above the danger zone. Finally, it would seem that this would be the proper way to take care of the manufacture of porcelain insulators. If the proper chemicals are chosen in the first place and the material is properly worked and properly fired, it will be necessary only to test it in such a way as to get rid of evident flaws. In the past there has been turned out a considerable quantity of imperfectly vitrified porcelain, and this is liable to be damaged by the tests which are made to discover the flaws.

In testing for flaws, it has been found that the high-frequency currents from an oscillating transformer produce a general stress over the whole surface of the insulator, each successive spark traveling over new surface of the porcelain skirts. Still further, we have found that by limiting the potential of the oscillating transformer, the strain on the porcelain can apparently be made even less than on the 60-cycle test. This is due to the fact that the higher frequency favors the production of creeping sparks along the surface. With the same applied potential the creeping spark will extend farther as the frequency increases. At the same time, the dielectric losses in the porcelain will increase as the frequency increases. Herein are the relations

which should be carefully studied. There is an evident probability that a high-frequency test can be made which will not strain good porcelain but which will tend to develop and pick out accidental flaws in the material.

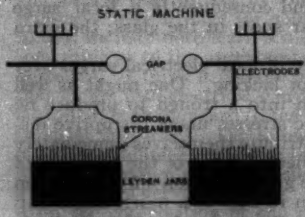


FIG. 2

In the foregoing criticisms it is evident that we have started from the point where the electrical engineering leaves off, namely the point of design; it has been stated many times that an insulator should be so designed that it will spark around the skirts rather than puncture the porcelain.

I want to emphasize a point brought out by Mr. Thomas in his remarks relative to the frequency at which the insulator is to be used. Actually, when you consider the use of the insulator, it is never over-strained at 60 cycles or 25 cycles. It is strained by lightning frequencies and by the frequencies that occur through accidental arcing grounds, and it is for that reason I think that all testing should be done with high frequency. The failures of insulators, outside of the effects of mechanical strains, can be attributed entirely to lightning and arcing grounds.

Some potential tests made a few years ago with panes of glass in air and in oil seem to answer the question of Mr. Koganei. If an ordinary piece of window glass in the air with the electrodes on the outside of it, is subjected to potential stresses, it is possible to raise the potential to a higher point than if it is immersed in oil. We made a series of tests to determine the reason for this and came to the conclusion that it was not due to the distribution of potential around the electrodes, but was due to the safety-valve effect of the corona streamers that run along the surface of the glass in air but not when it is immersed in oil.

Consider the ordinary conditions in a disruptive curcuit as shown in Fig. 2. The potential is built up by direct current until the gap is bridged and then the oscillation takes place in this circuit. At the instant of disruptive discharge there will be seen on the surface of the glass jars a tremendous number of little streamers which emanate from the metal covering. These little streamers are the relief valves that protect the glass from puncturing.

If the jars are immersed in oil and filled with oil, the corona streamers are almost entirely suppressed and a puncture of the glass will take place for a smaller gap setting than when the glass is surrounded by air. The corona itself forms extra surface, adding to the electrostatic capacity of the jars. Any sudden local surge thus relieves itself by creating a larger capacity and thus lessening the potential that would otherwise occur accord-

ing to the fundamental law $E = \frac{Q}{C}$. When the corona is suppressed there is no relief valve and consequently a local surge will hammer harder on particular spots in the glass; the extra strain will cause a puncture.

The indications of the existence of local electrical surges over the surfaces of condensers are not lacking. One might as well expect a bucket of water thrown into a trough to produce no splashing as to expect the electric stresses under disruptive discharge to gently and smoothly distribute themselves immediately in the condenser. As an experimental proof of the existence of local surges the following facts are given. When only one leyden jar on each side is used as shown in Fig. 2, a much larger gap can be made to spark without puncturing the glass than if many are used on each side. It was determined that this effect was not due to weakness of several of the many jars used.

Ralph D. Mershon: It seems to me that a question that has been raised before should be emphasized a little more, that is, as to the object of such specifications as these. These are specifications under which insulators are to be purchased from the manufacturer, unde which he is to supply them. Then it seems to me, as pointed out by Mr. Sandford, that all the questions of designs, form of insulation, flash-over, and that sort of thing should be determined before the contract is let, and then forgotten. That is a matter which we cannot usually specify, it seems to me. Our object in preparing any specification, and recommending one, if we are to recommend one, is not to enable engineering work to be automatically done, but these specifications are prepared and are to be used as a guide in procuring any given product determined on.

The preliminary determination as to design and the characteristics that will be given presumably to all the units is one that should depend upon the judgment of the engineer. If it were possible to determine all the characteristics, then it would not be necessary to have any tests at all, perhaps, or any specifications except some rough ones of a general nature, but it is not possible to determine in advance all the characteristics. You cannot lay down a hard and fast rule for the puncturing of the insulators, for instance, in the matter of test under oil, so that it is necessary to draw up specifications which will bring about the production of an article along commercial lines and in very reasonable approximation to the kind of product we are after.

Closely connected with that is the proposition made by Mr. Nicholson in regard to going into the ceramics of the matter. My advice in that connection would be general. I have made a little study of the side of this subject which relates to ceramics, and my experience so far has been that the more deeply you study it the less you know. You will find that the art of ceramics today is hardly on an engineering basis. It is approaching that,

and we have ceramic engineers, but the ceramic engineers meet serious obstacles every once in a while, as I know. There is a suggestion I might make in place of the one which has been made, and that is that we get in touch with our friends, the ceramic engineers, and arrange for some joint meetings on this matter, so that we may both learn something. On our side we will learn something as to the uncertainty of the manufacture of electrical porcelain. I think it is more uncertain than any other material that enters into electrical construction, and our knowledge of it is limited, both in regard to the electrical properties and the mechanical properties. Our knowledge of the mechanical properties is a very indefinite one at the present time. We have but very little information on the tensile strength of porcelain, and such as we have is very conflicting. It depends very greatly not only upon the composition of the porcelain but upon its mechanical treatment during manufacture. For instance, I presume a good many of you would assume that the tensile strength of porcelain, or ceramic material, because some of it is not worthy of the name of porcelain, increased with the vitrification. Now, that is not necessarily the case at all. Some of the strongest objects, that is, strongest with relation to tensile strength, made of ceramic material that I ever tested, have been the most porous and the ones most easily broken by a little knock. I remember one sample of porcelain which was tested up to 2200 lb. per sq.in., which is very high, and someone knocked this piece of porcelain on the floor and it broke into three pieces.

There are a lot of problems which are yet to be solved in regard to ceramic material, both from the chemical, electrical and mechanical side, and it is a pretty complex problem. I think Mr. Mailloux's remarks in that respect were well to the point.

To my mind one of the most important tests is the puncture test under oil, but when you come to apply it and use it as a criterion as to the quality of product, it is extremely difficult to determine how it shall be applied. Mr. Sandford has mentioned the percentage of the product which shall be tested under oil. All right, but suppose you test it under oil and it falls considerably below what you expect it would do, and what the tests of the first samples had encouraged you to believe you would get. What are you going to do about it? Say you have a large order of insulators to be got out on time, and the manufacturer doing the best he can, and his material is considerably below the puncture test you thought you were going to get. It is extremely puzzling to know what to do. You cannot test all of your insulators, that would be almost prohibitive as a matter of course, and few manufacturers have the facilities so that you could test them all under oil. In one case in my own experience we did this—we assumed we could not ask the insulator manufacturer to do any better than it was possible for him to do. The most we could ask then was that we should get as good porcelain as anyone else got. The particular insulators in

question had a lower flash-over value than some others being turned out, so that if they were tested in air they would be tested at a lower voltage as regards puncture than the other insulators being turned out. We could not tell then, from a test in air, as to whether the porcelain in these insulators was as good as that in the others. When we came to make the test under oil, if the puncture values were lower than we thought they ought to be, we agreed that we should have the right to test some of the other product that was going through the factory and which was passing the routine test through air, under oil, and if ours tested out as good as they did, then we were subject to negotiations, even though it was not as good as we thought. If it was not as good as that, we were in the position under the contract to exert some considerable influence. That was agreed upon.

It may be possible to work out some better arrangement, but it is exceedingly puzzling to know how to control your product, when you can only test a small part of it, and when you are dealing with a product which is notoriously non-uniform. On this matter of uniformity I agree with Mr. Peek. I would rather have insulators which run very uniformly in a lot tested, even those in which the puncture value was considerably lower than might be obtained with some other product which was less uniform.

There is one thing Mr. Peek mentioned which I would like to discuss further, and perhaps get some further information on the point, and that is the objection to using the sphere gap in making the insulator tests. He suggests it would be better to calibrate the transformer. I think in many cases it would be, but my reason would be that of convenience. His reason was not quite clear, that was, in making the end test on the insulator the voltage on the spark gap might be higher than otherwise. It seems to me the insulator gets the same voltage as the spark gap does, if the apparatus is properly collected up and located, and I cannot see, from that standpoint, the objection to using the sphere gap.

It seems to me it is important to have the wet and dry tests as nearly the same as possible, so that the idea of specifying the flash-over test dry shall be at least equal to a certain amount seems to me is a little bit irregular. I should say that the most logical way to specify it would be with reference to the wet flash-over test. It seems to me the precipitation in some specifications is pretty high. One inch depth in five minutes would occur to me to be amply high enough for most, if not all, places in the United States. That is considerably higher than the maximum precipitation ever recorded by the U.S. weather bureau. If you want to add a factor of safety, do not add it through the precipitation test. I think it is better to add it through the voltage to be impressed on the insulator. Also in regard to the matter of precipitation, I hope there will be some further discussion on Mr. Thomas's suggestion of inclining the insulator

and using a vertical spray instead of a spray at an angle. It is difficult to get a spray at an angle which will be uniform and accurately directed. It would be much easier to accomplish the same conditions with a vertical spray and the insulator at an angle. The objection may be made that that does not simulate the conditions of practise. In reply to that you can say that we do not know much about what the conditions of practise actually are, and there is considerable question as to whether the 45 deg. spray simulates them any better than any other method of procedure would. In any case, what is the difference provided we have certain values which we know approach the practical value of the insulator? Is it not much better to have a condition of test which we can repeat with some assurance of accuracy even though it does not simulate completely the conditions of practise?

There is nothing said about cement—how the insulator shall be handled after it is cemented. In the first place, it should not be used soon after cementing, and should be kept above the freezing point. I know of some pieces of work in which the insulators were allowed to freeze before they set and when they got out on the line there was some trouble. That was a case where it was not possible to test the insulators as a completed whole, and they had to be tested in separate parts. When you test them after assembling, that point is not of such great importance, except that it is always important not to have your deliveries held up by the failure of a lot of insulators, and, of course, that is important from the manufacturer's standpoint, not to lose a lot of the product.

I should also like very much to hear from the insulator manufacturers as to the absorption tests which have been proposed, whether or not they are satisfactory to them, whether they are too difficult, or whether they are likely to result in a product whose existence is not justified.

I would also say that I agree with Mr. Nicholson in his remarks in regard to the flash-over values of the insulators. It seems to me that a desirable insulator is one which will flash over the unit always before it will puncture. If that is the case, why not space your units far enough apart so that approximately, at least, you get the benefit of the full value of each unit? If there is a power arc-over, as a rule it will go to the outside plenty quick enough. I doubt if you will find any difference in the breaking of the insulators whether the power arc starts around the insulators or between them. If the amount of power is enough to break the end unit, it may go along a line of insulators, a string of units, if the arc persists long enough. Whether it flashes clear around the string, or starts clear around individual units, there is little difference in practise, so far as we have been able to observe.

Percy H. Thomas: President Mershon was the one who suggested having the spray vertical and the insulator at 45 deg.

Of what effect, in one of these specifications, would be the provision that we separate the design test from the routine test, as you suggest? What would you have done with the specification?

Ralph D. Mershon: I would place the most stress upon those things which will control the product as we go through the process of manufacture. I do not think I would put the matter of design in the form of a specification at all. I do not see why we should supply specifications for the design of the insulator at all. It is likely to impair progress, I think, and in any case the engineer in charge of the work ought to have enough knowledge and experience to exercise his own judgment in regard to questions of design. The usual course is to get samples from the different manufacturers and test them. If there are any new designs which have been brought out, you can compare them with regard to corona and in regard to string ratio, and all of the other points that are involved in the design of the insulator itself and in regard to the puncture value of the insulator. After you have done that, you want a specification to which you can fairly require conformity, and it will result in bringing forth as uniform a product as the state of the art will permit.

Percy H. Thomas: Is not that exactly what we have in the first specification? We have the routine test separated from the design test in a perfectly plain manner. The first part may not be called a specification, but have these things stated, and call attention to the necessity of uniformity in the product and leave the greatest freedom for variations in design. We do not limit the development of the art, but want to call attention to the way tests should be made, and things of that sort. I agree with you in the matter.

Ralph D. Mershon: The remarks I would add in regard to that would be directed more against the supplying of specifications for design at all. Any specifications we agree upon should be directed toward bringing the product through and not to the matter of the design of the product.

E. M. Hewlett: I think that the last point Mr. Mershon brought out is one of the most important. The general design of the system should be settled before any decision is made as to the particular insulator which should be used. The proper insulator to use will be determined by the voltage of the line. An insulator designed for a 70,000-volt line would naturally show corona at a lower point than an insulator designed for a 100,000-volt line. Also, insulators designed for any given voltage at a given altitude will show corona at a lower voltage at higher altitudes. Thus at points where a line crosses a mountain range it might be necessary to use insulators of a different design than those used at lower points so that all the insulators will show corona at about the same voltage.

In reference to the arc-over test, we find that many manufacturers consider a puncture or a flash-over test with a testing transformer equivalent to an actual line test, but Mr. Mershon has

shown the fallacy of this. He brought out the point that whereas you might flash over and strike between the insulators and probably break the whole string, the power arc-over, that is, the arc-over on a power system, as distinguished from a flash-over on a testing transformer, often improperly called a power arc, would probably throw clear of the insulators in an instant. If the insulators fail it may be because a w nd is blowing at the time, whereas a similar flash-over clear, without adverse wind, might not have created any trouble. The flash over the entire string of insulators might have been blown into the string of insulators if it had been drawn in by a flash in between.

In reference to the rain test, the 45-deg. angle test, the amount of water, etc., I find that many times tests are run with an abnormally large amount of water, a great deal more than actual precipitation conditions justify, the insulators being first tested under actual precipitation conditions and then, if they do not arc over, the amount of water is increased until the insulators do arc over. It would seem a much better test to duplicate actual precipitation conditions, increasing the voltage until a flash-over results, because this method gives a better idea of the behavior of the insulators under actual conditions. It should be obvious to everyone that when excess water is used, the information being sought from the test is not and cannot be obtained, which is the maximum possible arc-over voltage at maximum rain conditions and not at five times this point.

Now considering the rain test at an angle of 45 deg. If rain is falling at 45 deg. there is considerable wind, and if the wind condition is not duplicated in the test, the water will stream over one disk to another and the insulators will flash over at much less voltage than they would under actual weather conditions because of the wind blowing the streams of water so that they will not drip from one disk to the next one below it.

Then there is another point. We have seen tests where the insulators were damaged because they were too far apart, whereas the individual test on each disk was good. Because the insulators were placed a little far apart, they flashed around the individual disks, whereas if they had been placed closer together the flash would have been around the whole string. Also insulators are often arranged simply to meet the ideas of the engineers testing them, making the test a personal rather than a physical equation.

In reference to the absorption, while 0.01 of one per cent in porcelain is possible, I doubt whether this absorption can be maintained at this time in the case of large orders, because there is a difference in the temperature in different parts of the kiln, as well as in the different burnings, etc. If you demand 0.01 of one per cent absorption, I think it probable that the cost will be increased.

On the basis of cost, I think also that the tests suggested are too long, and that too many insulators are tested. The purchaser will have to pay the additional cost, it has to go

somewhere, and if the insulators are subjected to severe tests and long tests, which entail some hardship on the manufacturer, the extra expense must naturally be put into the price of the product.

The altitude is not considered in the specifications, and I do not suppose that it should be, but a reference should be made so that it will be remembered by engineers selecting insulators for higher altitudes. In this connection, if only a small portion of the line runs at a higher altitude it would be a hardship to make a specification for this altitude include all the insulators which are used at the lower altitude.

P. H. Thomas: I think you are right about that.

E. M. Hewlett: Regarding the appearance of the corona at different altitudes—an insulator of a given design and with a certain size pin will show corona at a definite altitude with given climatic conditions, and some reference should be made to this so it will be considered in selecting insulators for various altitudes. There should be a practical specification drawn up for the inspector's use, so that he can determine whether the insulators received are made of the proper material and are of the dimensions called for, etc., and that they will pass certain electrical tests. I also believe that specifications should not specify the details of manufacture, because no good would be accomplished. It is always to the interest of the manufacturer to work out efficient methods of design and manufacture to accomplish the various purposes desired and he is often not in a position to manufacture, without added expense, according to other methods which might be specified. If you limit the man in the porcelain factory in the making of porcelain or seek to influence the way in which he handles his materials, you are going to handicap him seriously, because some clay combinations are more suitable for thick bodies and some for thin bodies, and the characteristics of the clay must be considered in working out a design for a given purpose.

In reference to the porcelain, I have been working out different designs of porcelain for the last fifteen or eighteen years, and I agree with anything that anyone says about the varying character of the product. We make insulators of various kinds, as it is necessary to do so in order to obtain the different forms which are required. It is often difficult, if not impossible, for us to obtain just what we need from outside manufacturers. From experience I have found that the ceramic engineers and foremen in charge of the porcelain factories often unintentionally mislead us as to the form in which it is possible to make given insulators. There are many factors to be considered in manufacturing porcelain that do not occur in other lines, and it takes a great deal of experience with the design and manufacture of porcelain and its uses for one to be reasonably able to predict what results will be obtained from various designs.

As to the advisability of making up the strings of units which will not flash over before the line potential is reached, this may be feasible for some voltages, but it is obvious that after a certain voltage is passed it will not be practicable. For instance, it would be difficult at the present time to make up a string of insulators for a 140,000-volt transmission line in which each unit in the string could be tested to flash over at line voltage, 140,000 volts. Such a design would be practically prohibitive.

The specifications given for suspension insulators often call for strength far in excess of the strength of the conductor and the possible strains on the system, and consequently introduce a factor which may call for a design of insulator electrically inferior, though testing mechanically stronger than is necessary, whereas if the specifications did not call for these excessive strengths, better electrical characteristics could often be secured. It should be kept in mind that the initial strain which an insulator will stand does not necessarily prove that it will maintain this great strength over a long period. Some insulators that have stood great strains at first have been known to drop the conductor in a comparatively short time after having been put in service and having been subjected to only a small portion of the original testing strain, due to the methods of fastening the links together.

As to the mechanical test, I think the points made by Mr. Sandford and Mr. Nicholson about this are correct. I think they should be made as general tests, though, and only a comparatively small number would be necessary to test in that way. You ought to test your design in that way, the same as you would for other designs, and then run at a proper safety factor and use enough strain insulating sections in multiple to get the desired strength. Then as to the suspension insulator. A suspension insulator is not ordinarily called upon to stand so much strain as a strain insulator, even under emergency conditions, as the suspension insulator is nearly always put on the lighter tower, and if subjected to the same strain as the strain insulator the tower would probably be pulled over.

H. W. Crozier: I want to say a word in regard to the matter of vitrification. There are two kinds of tests, one a general test as to the material you are going to get and another a detailed test of each particular piece of porcelain. There is nothing said whatever in the specification about the vitrification test of each particular piece of porcelain. When I first learned something about the porcelain business, Mr. Sandford was working on the same problems. We would set up a long row of insulators for test and very quickly the inspector learned to pick out pieces of porcelain which were not thoroughly vitrified. Many pieces, however, were doubtful and it was found that soaking in a tub of water over night had a very great influence on the insulators. A large proportion selected by the inspector as doubtful would fail after the soaking test, showing insufficient vitrification.

As has been said here, the manufacture of insulators is not by any means uniform, and from any one kiln you can take insulators which are very fine and right alongside of them you will find insulators which are not vitrified. After a little experience, the suspected ones are picked out and set aside, and sent back to the oven and refired, and by that means the manufacturer saves the loss which would be caused by their failure. I would like to see something put in the specification to cover this question of test for the vitrification of individual pieces. I think the best way to do that is to take the porcelain and soak it in water—that would be the test which I should apply. Whether we should require this 0.01 per cent of absorption, I do not know, but soaking in water will soon determine. We can get a porcelain insulator which will stand the electrical test, but we want to be certain that the insulator will not deteriorate in service. In the same lot of insulators that I have spoken about we did have a large number of insulators deteriorate in service. That was due to the fact that the insulators were not thoroughly vitrified. They were made in a new factory and no one had sufficient experience to properly select the insulators which were not thoroughly vitrified. If these insulators had been soaked, I believe not many would have passed the test. After the line had been in service about two years, one section of the line where the first four carloads were used was found to give a great deal of trouble due to failure of insulators.

As to the other question raised about the strain insulators, in regard to the mechanical test, words have been put into my mouth which I did not use. I anticipated we would use two different types of insulators. If we are going to apply additional tests to a lot of insulators, we will naturally raise the price, so it would be better to have one lot of insulators for the strain insulators and another lot of insulators for the span insulators. If the span insulators are accidentally seriously loaded, and break in the line, that is a very serious matter, but one which should be carefully considered in the design. As a rule, for heavy loads it is better to use two or three strings of insulators in parallel for strain insulators.

P. W. Sothman: The problem before us is one that cannot be disposed of by following ordinary thumb rules. To me, every insulator represents an integral part of a system, requiring a special study for each individual installation. For it is obviously impossible to select an insulator for a certain service and then assume that this same insulator will withstand any other service under any other conditions, on the strength of the fact that the voltage of the line is the same.

I believe it would not be wise to draw up specifications for the manufacture of insulators by setting cast-iron rules for the manufacture and testing. What is most needed in these specifications is well-defined principal requirements. And, further, I believe the manufacturer and the engineer should arrive at a

mutual understanding as to how the best results can be obtained. I think one of the most advantageous things from a practical point of view which we can undertake to do is to urge the manufacturer to improve the character of the porcelain, in order to obtain a more uniform product.

Mr. Peek has advanced several points which can only be viewed from a purely academic standpoint, and Mr. Sandford has given us his views from the manufacturer's standpoint. Mr. Sandford does not wish the engineer to settle all questions, but wants to give us what he thinks best and not necessarily what we need. I think we should specify clearly what we need. But do not let us step in and tell him how to do it. It is his business to know that.

With reference to the tests of the insulators, it appears that tests on dry and wet insulators vary considerably. I do not believe that any of our practical engineers have ever seen an insulator fail under a wet test, and in spite of this they still specify wet tests. It was pointed out, and I think it was endorsed by Mr. Sandford, that the water used for these water tests has a range of 100 per cent in conductivity. Mr. Mershon remarked that some water was a good insulator and other water a good conductor, and I have always found that to be the case. I have seen wet tests on insulators that did not leave anything to be desired; however, when the insulators were tested in another room, they failed entirely, under apparently the same test.

I absolutely agree with the remarks of Mr. Lincoln, who recommends the use of water from condensed steam. I agree with him that we should approximate as closely as possible the natural conditions, in specifying our tests. There is nothing gained by overstressing the insulator to such a point that it will fail soon after it is placed on the line. We want a commercial piece of apparatus, and for this reason we will have to be less academic and more practical in calling for something which will satisfy the operator. Now, to obtain these conditions, if the gentlemen who are in charge of the practical operation of a transmission line will join hands and heads with the insulator manufacturer, and study the subject thoroughly, we would be sure to obtain better results, and for that reason I would suggest that a resolution be passed turning over the work of the gentlemen who have presented these specifications to a committee to be appointed to work out the details in coöperation with the manufacturers, in order to avoid the danger of framing a specification that would do more harm than good. It should always be borne in mind that a chain is only as strong as its weakest link. The breaking down of insulators does not necessarily imply that the insulators, themselves, are at fault. In a good many cases, the trouble has its seat elsewhere. Distribution of stresses along the string of insulators and at their extreme ends, the design of cable clamps, its protection, etc., etc., all must be duly considered. Until all troubles and their causes are clearly

understood and their relative value appreciated, both qualitatively and quantitatively, nothing can be gained by blindly adding material to an insulator with the object of making it safer against these causes.

C. F. Scott: The problem seems to be a triple one: first to determine, by research, what it is possible to secure in the way of satisfactory insulators; second, to determine, by research, what characteristics an insulator should have in order to be wholly satisfactory; and third, a commercial test to determine whether particular insulators meet these requirements, and conditions. The three elements are—research, engineering and commercial testing.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING

BY F. D. NEWBURY

Considerable information has been presented before the Institute and elsewhere concerning the performance of self-starting synchronous motors, but this has dealt mainly with the mathematics of initial starting torque and current and the performance under a few of the simpler conditions of starting voltage, load and excitation. There is much more than this involved in the complete starting operation, and the purpose of the present paper is to describe—from the physical point of view—what actually takes place in the motor windings under a wider range of starting conditions. The information presented in the form of oscillograms is not only interesting in its bearing on synchronous motor operation, but as experimental data illustrating principles common to alternating-current circuits in general.

Two machines have been used in the experiments described: a 200-kv-a., 2400-volt, three-phase, 600-rev. per min., standard belted generator and a 150-kv-a. generator of the same characteristics and of the same general design. These two generators have the same number of poles and rotor diameter and, in fact, use the same rotor punchings, so that the design proportions are very closely the same. Both generators are provided with a copper damper winding of the general type shown in Fig. 1. These machines, having been designed as belted generators, have only average performance characteristics as self-starting synchronous motors. The damper winding is of low resistance to serve as a damper during synchronous operation, and as a starting winding for usual synchronous-motor applications where the initial starting torque is not large.

The complete starting operation may be conveniently divided into three parts, as follows:

1. Motor starting from rest at reduced voltage and no excitation.

2. Motor running on partial voltage without excitation in synchronism; excitation then applied.

3. Motor running on partial voltage, excited, and in synchronism; voltage then increased to normal line voltage.

There are two additional variations of the third part of the starting operation which can most conveniently be classed as additional parts, as follows:

4. Motor running on partial voltage, without excitation, with external load, field not excited and motor not in synchronism; field then excited and synchronism attained and full voltage applied.

5. Motor running on partial voltage, with external load, excited, but not in synchronism; line voltage then applied and synchronism attained.

The subject will be treated under headings corresponding with these five parts of the starting operation.

I—Motor Starting from Rest at Reduced Voltage; No External Load

(a) *Field Circuit Open.* This condition is shown by Fig. 2. The motor is started by the application of approximately $\frac{1}{3}$ normal voltage with the field open-circuited and with no external load. A shunt transformer, connected across the field terminals, affords a record of the voltage by the oscillograph. It will be noticed that the maximum current of 106 amperes resulting from the application of voltage is maintained at an approximately constant value until the motor is well up to synchronous speed. The voltage induced in the field winding, as is well known, is a maximum at start and has a frequency equal to that of the supply circuit, the frequency gradually decreasing until it becomes zero when the motor is in synchronism. The voltage is proportional to the rotor frequency, or slip.

(b) *Field Circuit Closed.* The conditions shown by Fig. 2 are duplicated in the oscillogram Fig. 3, except that the field is closed through its rheostat, the combined resistance of the rheostat and field winding being approximately 8.5 ohms. The armature current is slightly increased, having a value of 120 amperes instead of 106 amperes. A current of 10 amperes (maximum

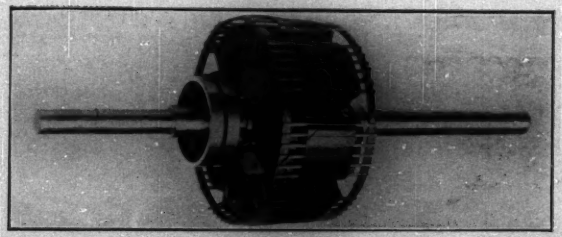


FIG. 1—TYPE OF DAMPER CONSTRUCTION [NEWBURY]

[NEWBURY]

FIG. 2—OSCILLOGRAM SHOWING STARTING CONDITIONS WITH ½ VOLTAGE, NO EXTERNAL LOAD, *Open* FIELD CIRCUIT, 150-KV-A. MOTOR

Upper record motor voltage. Middle record armature current in one phase. Lower record field *voltage*.

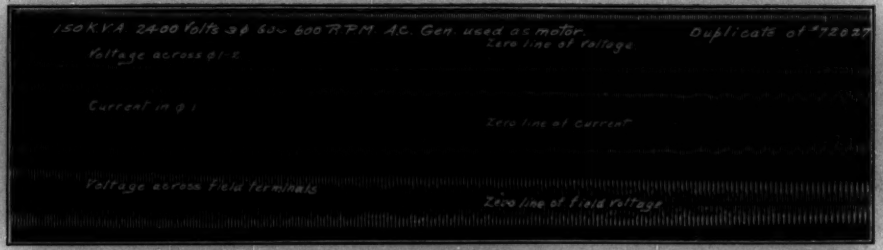


FIG. 2—(*Continued*)

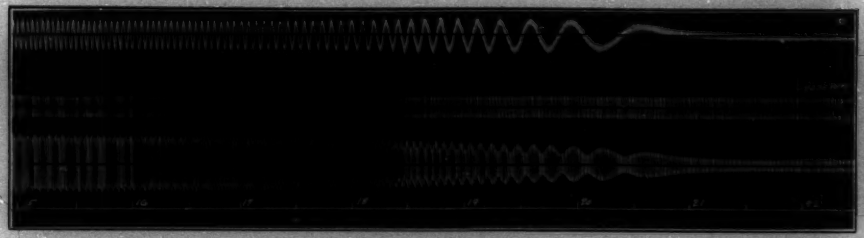
FIG. 2—(*Continued*)

[NEWBURY]

FIG. 3—OSCILLOGRAM SHOWING STARTING CONDITIONS SAME AS FIG. 2 EXCEPT *Closed* FIELD CIRCUIT, 150-KV-A. GENERATOR

Upper record motor voltage. Middle record armature current. Lower record field *current*. Printed oscillogram does not show first few seconds of starting.

FIG. 3—(*Continued*)



[NEWBURY]

FIG. 4—OSCILLOGRAM SHOWING STARTING CONDITIONS WITH ½ VOLTAGE, NO EXTERNAL LOAD, CLOSED FIELD CIRCUIT, 200-KV-A. MOTOR

Upper record field current. Middle record motor voltage. Lower record armature current. Printed oscillogram does not show first 15 seconds of starting.

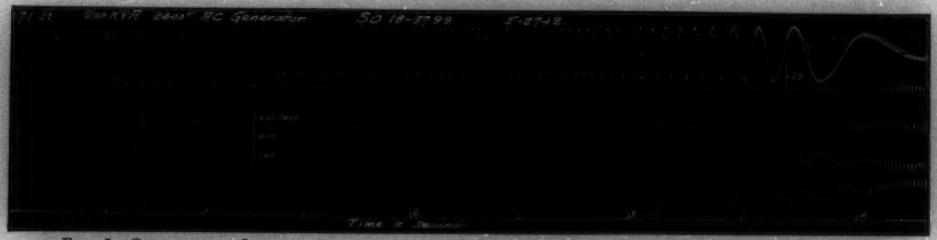


FIG. 5—OSCILLOGRAM SHOWING SAME STARTING CONDITIONS AS FIG. 4 EXCEPT ¾ STARTING VOLTAGE [NEWBURY]

Motor reached synchronism in 5½ seconds as compared with 21 seconds in Fig. 4. Upper record field current. Middle record motor voltage. Lower record armature current.

value) is induced in the field winding and is maintained at this value until the motor is within a few per cent of synchronous speed. This field current is alternating, and, like the field voltage in Fig. 2, has a frequency equal to the slip. There is a pulsation in the armature current corresponding to the frequency of the current in the field circuit, these pulsations becoming very pronounced near synchronism. Although the value of the voltage induced in the field circuit is proportional to the slip, as shown in Fig. 2, the current is practically constant, due to the

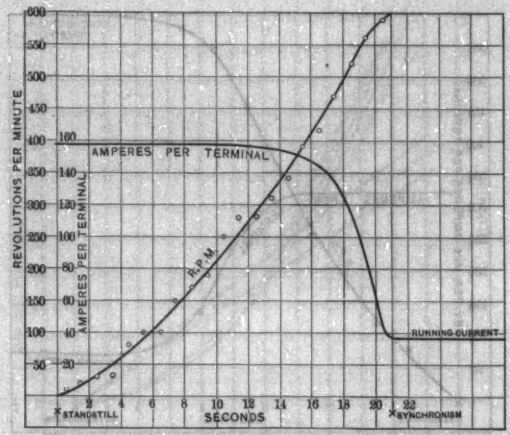


FIG. 6—SPEED AND CURRENT DURING STARTING UNDER CONDITIONS OF FIG. 4

reactance of the field winding and the voltage decreasing at the same rate. The constant resistance of the field circuit has a negligible effect until the reactance has become practically zero near synchronism. This illustrates very clearly the reason why resistance connected in the closed field circuit has practically no effect on the armature current and torque until the resistance has been made at least equal to the reactance at normal frequency. Figs. 2 and 3 show results from the 150-kv-a. motor. Similar results from the 200-kv-a. motor with closed field circuit are shown in Fig. 4, with $\frac{1}{4}$ normal voltage, and Fig. 5, for $\frac{3}{4}$ normal

voltage. The fact that the frequency of the current induced in the field winding is equal to the slip makes it possible to plot a curve showing the relation between speed and time. Such a curve plotted from the oscillogram in Fig. 4 is shown in Fig. 6 for $\frac{1}{3}$ voltage, and from the oscillogram in Fig. 5 is shown in Fig. 7 for $\frac{2}{3}$ voltage. To these curves have been added the current curves which illustrate the point already made, that the maximum current is maintained at a constant value until synchronism is nearly reached.

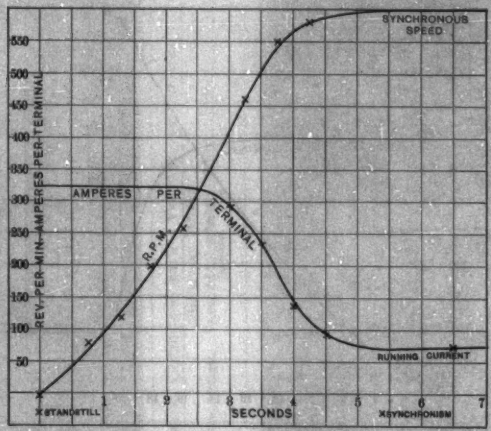


FIG. 7—SPEED AND CURRENT DURING STARTING UNDER CONDITIONS OF FIG. 5

The effect of the closed or open field circuit on the torque developed is shown in Figs. 8 and 9 for the 150-kv-a. motor. Fig. 8 shows the current and kilowatts existing when varying voltage is applied to the armature, the rotor being locked. Under these conditions, the observed kilowatt minus the armature loss represents the loss in the rotor, and this in turn is proportional to the torque developed at the instant of starting. With the field circuit closed, the loss due to the single-phase current in the field winding is not effective in producing torque, so that the two curves are not exactly comparable. The loss in the field winding,

however, is negligible, so that this fact does not appreciably affect the statement made. It will be noted that the rotor loss is slightly greater with the field short-circuited than with the field open-circuited, showing that the short-circuited field, at least, has not been a serious detriment to the development of torque.

In Fig. 9, the starting torque is shown directly as measured by brake-beam and scales for a 150-kv-a. motor of the same design, except with a different armature winding for 440 volts.

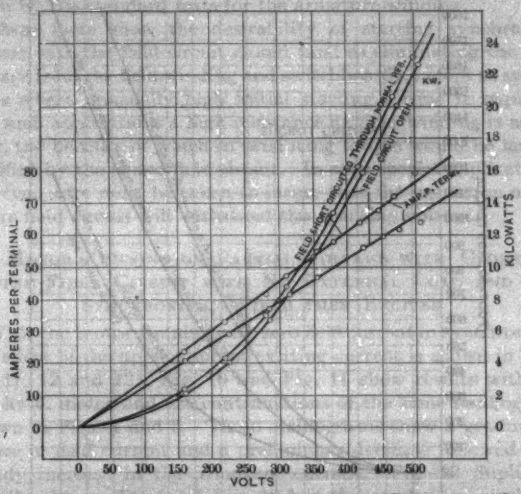


FIG. 8—COMPARATIVE STARTING TORQUE WITH CLOSED AND OPEN FIELD CIRCUIT—150-KV-A. MOTOR—COPPER DAMPER WINDING

The armature turns, however, in the two motors are proportional to the voltages. Torque curves are shown with the field circuit closed and with the same damper winding as used in the motor used in the oscillograph tests, and with a damper winding composed of brass bars instead of copper bars. With the latter damper winding, the curves show a material increase in torque with the field open as compared with the field closed.

Figs. 8 and 9 illustrate a condition generally true: that with an effective low-resistance damper winding, the torque and armature

current are very little affected by the closed field circuit, but that with a high-resistance damper winding, or with a rotor construction that permits only an ineffective damper winding to be used, the closed field circuit has a marked effect in reducing the initial starting torque. The field winding may be considered as an additional winding in parallel with the squirrel cage winding. Whether it has an appreciable effect in decreasing the torque for

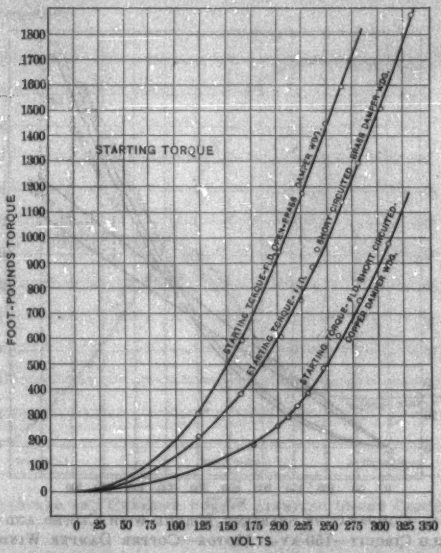


FIG. 9—COMPARATIVE STARTING TORQUE WITH CLOSED AND OPEN FIELD CIRCUIT, HIGH AND LOW RESISTANCE DAMPER WINDINGS

a given voltage depends simply on its resistance compared with that of the squirrel cage winding and the relative currents in the two windings. It is of interest to note that with a combination of field and damper windings such that the closed field winding has an appreciable effect on the torque developed, there is a considerable tendency for the motor to lock at half speed, the effect being the same as a phase-wound induction motor with one phase open-circuited.

It will be noted in Fig. 2 that the induced voltage has a value of approximately 4000 volts maximum, or 2800 volts, effective value. With a higher exciting voltage, requiring more turns in the field winding, or with a higher resistance damper winding, this voltage would have been considerably higher. For self-starting synchronous motors started with the field circuit open, the present standard insulation test of 5000 volts may be exceeded in many cases by the actual voltage obtained in operation, and in few cases does it give the same factor of safety that is given by the standard tests for the armature winding.

These facts show the desirability of starting synchronous motors with the field circuit closed (and so eliminating the high voltage from the field winding and switchboard), except in special cases where unusually high initial starting torque is required. For such applications a high resistance damper winding is necessary, the benefits of which in producing torque would be largely nullified by the closed field circuit. In such special applications, however, care must be taken to insure that the insulation of the entire field circuit will withstand the resulting voltage.

II—Motor Running on Partial Voltage with Closed or Open Field Circuit with No External Load and in Synchronism; Field then Excited

With the motor running with zero field current in synchronism, the effect of the application of exciting current is shown in Figs. 10, 11, 12 and 13. Fig. 10 and Fig. 11 show results with the 200-kv-a. motor and are continuations of the same oscillograms shown in Figs. 4 and 5. These oscillograms show a gradual increase in field current and a preliminary decrease followed by a steady increase in the armature current. Fig. 12 duplicates exactly the conditions of Fig. 10 but the results are markedly different. The armature current immediately starts to increase instead of first decreasing as in Fig. 10, and reaches its final value only after successive pulsations lasting 8 or 9 seconds. The field current, instead of steadily increasing to its final value as in Fig. 10, pulsates synchronously with the armature current. When steady conditions are attained, however, the values in Figs. 10 and 12 are substantially the same. Fig. 13 shows a similar result with the 150-kv-a. motor.

An examination of a large number of oscillograms taken shows no fixed relation between the occurrence of the steady increase in field current and armature current as in Fig. 10 or the pulsating

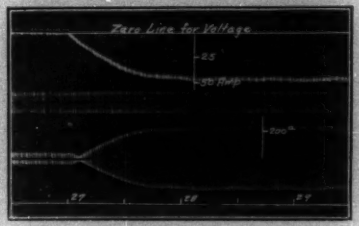
increase as in Figs. 12 and 13, and other conditions of operation. The most reasonable assumption is that the steady increase occurs when the field current and armature current at the instant of closing the field switch agree in polarity, and that the pulsating condition occurs when they do not so agree. The immediate increase in armature current in Fig. 12 when exciting current is applied is, under this assumption, required to maintain the necessary net excitation required for the applied voltage and flux. The succeeding decrease in armature current is caused by the rotor "slipping a pole" to bring the armature and field excitations in phase. The relative change in armature and field polarity requires a decrease in field excitation to maintain constant, flux, as shown by the oscillogram. If, when the rotor "slipped a pole," it remained in synchronism with the armature, the armature and field currents would gradually increase to their final steady value, as in Fig. 10. The succession of pulsations shows that the rotor oscillates back and forth, succeeding oscillations decreasing in amplitude until the rotor settles into its final relative position.

In all of the oscillograms so far shown, the excitation has been much more than that required to maintain minimum armature current with 100 per cent power factor, so that the final steady value of armature current has been greater than that required with zero rotor excitation.

III—Motor Running on Partial Voltage, Excited and in Synchronism, With and Without External Load; Line Voltage then Increased to Normal

This condition is shown by Figs. 15, 16 and 17, representing an initial voltage $\frac{1}{4}$ of normal and no external load on the motor; Figs. 18, 19 and 20 representing an initial voltage of $\frac{2}{3}$ normal and no external load on the motor; and Figs. 21 and 22 representing an initial voltage $\frac{2}{3}$ of normal and with approximately $\frac{1}{4}$ full load on the motor.

The change from the initial starting voltage to normal voltage is made by a double-throw switch. The armature circuit is momentarily opened in throwing from the low voltage to the high voltage and current drops to zero during this interval. The voltage, instead of also dropping to zero, as might be expected, increases or decreases, depending on the value of the field current. During this same interval the field current shows a marked decrease in some cases and an increase in other cases due to change in armature current.



[NEWBURY]

FIG. 10 — APPLICATION OF EXCITING CURRENT. CONTINUATION OF OSCILLOGRAM FIG. 4. ½ VOLTAGE, 200-KV-A. MOTOR

Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature current.

[NEWBURY]

FIG. 11—APPLICATION OF EXCITING CURRENT. CONTINUATION OF OSCILLOGRAM FIG. 5. ½ VOLTAGE, 200-KV-A. MOTOR

Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature amperes.

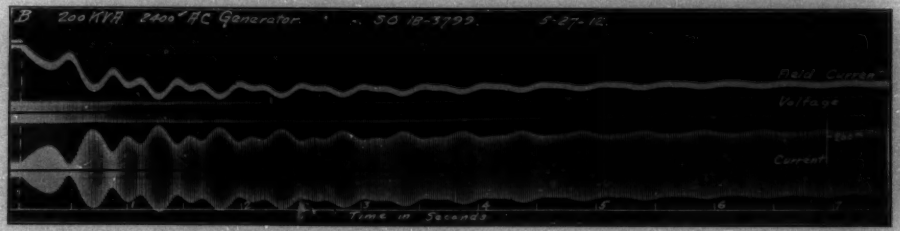
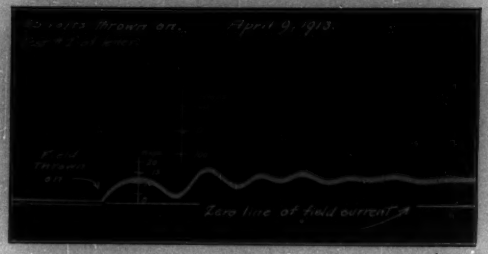


FIG. 12—APPLICATION OF EXCITATION [NEWBURY]

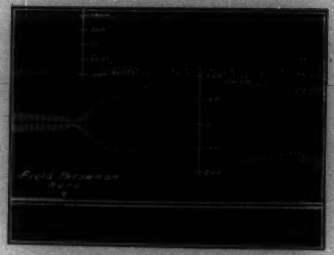
Same conditions as Fig. 10—pulsating current increase instead of steady current increase. Upper record—field current—positive values below the zero line. Middle record motor voltage. Lower record armature current.



[NEWBURY]

FIG. 13—APPLICATION OF EXCITATION. CONTINUATION OF OSCILLOGRAM FIG. 3. ½ VOLTAGE, 150-KV-A. MOTOR. PULSATING CURRENT INCREASE

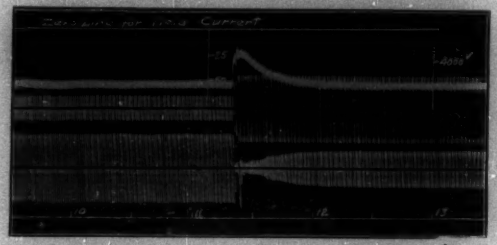
Upper record motor voltage. Middle record armature dampers. Lower record—field amperes—positive values above the zero line.



[NEWBURY]

FIG 14—APPLICATION OF EXCITATION. CONTINUATION OF OSCILLOGRAM FIG. 2

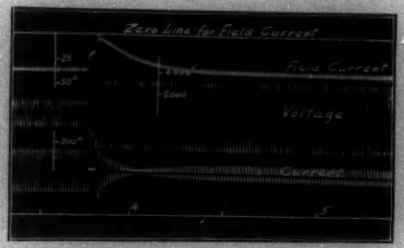
Same conditions as Fig. 13 except field open circuited. For this reason there is no record of field current when field is excited.



[NEWBURY]

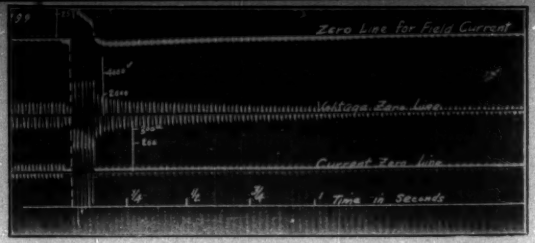
FIG. 15—APPLICATION OF LINE VOLTAGE—CONTINUATION OF OSCILLOGRAM FIG. 2. ½ STARTING VOLTAGE 47.5 AMPERES FIELD CURRENT, NO EXTERNAL LOAD, 200-KV-A. MOTOR

Upper record—field current—positive values below zero line at top of record. Middle record motor voltage. Lower record armature current.



[NEWBURY]

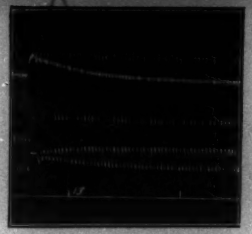
FIG. 16—APPLICATION OF LINE VOLTAGE. ½ STARTING VOLTAGE 32.5 AMPERES FIELD CURRENT. NO EXTERNAL LOAD—200-KV-A. MOTOR



[NEWBURY]

FIG. 17—APPLICATION OF LINE VOLTAGE. ⅜ STARTING VOLTAGE, ZERO EXCITATION—CLOSED FIELD CIRCUIT—NO EXTERNAL LOAD—200-KV-A. MOTOR

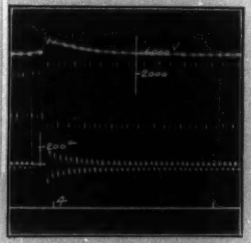
Sudden reduction of current to zero is due to accidental opening of circuit breaker.



[NEWBURY]

FIG. 18—APPLICATION OF LINE VOLTAGE, ⅜ STARTING VOLTAGE, 47.5 AMPERES FIELD CURRENT—NO EXTERNAL LOAD—200 KV-A. MOTOR

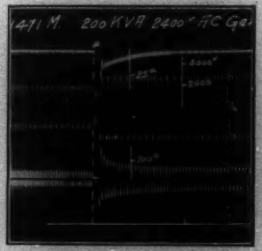
Upper record (superimposed on middle record) field current—positive values below zero line (not shown on printed section of oscillogram). Reduction in field current when line switch is closed is approximately 26 amperes. Middle record motor voltage. Lower record armature current.



[NEWBURY]

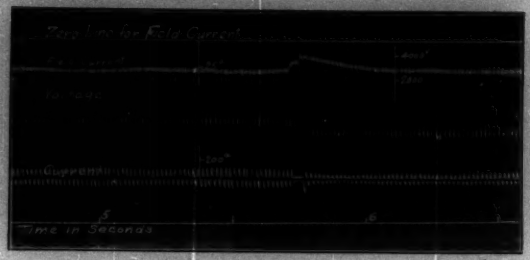
FIG. 19—APPLICATION OF LINE VOLTAGE. ⅜ STARTING VOLTAGE, 26.5 AMPERES FIELD CURRENT—NO EXTERNAL LOAD—200-KV-A. MOTOR

Upper record—field current—positive values zero line (not shown on printed section of oscillogram). Minimum value of field current when line switch is closed is four amperes. Middle record motor voltage. Lower record armature current.



[NEWBURY]

FIG. 20—APPLICATION OF LINE VOLTAGE. ⅜ STARTING VOLTAGE, ZERO FIELD AMPERES—CLOSED FIELD CIRCUIT—NO EXTERNAL LOAD—200-KV-A MOTOR



[NEWBURY]

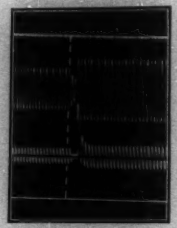
FIG. 21—APPLICATION OF LINE VOLTAGE. ⅔ STARTING VOLTAGE—27.8 AMPERES FIELD CURRENT. 70 KW. LOAD ON 200-KV-A. MOTOR

Compare with Fig. 19—same conditions except load.

[NEWBURY]

FIG. 22—APPLICATION OF LINE VOLTAGE. ⅔ STARTING VOLTAGE, ZERO FIELD AMPERES, CLOSED FIELD CIRCUIT. 70 KW. LOAD ON 200-KV-A. MOTOR

Compare with Fig. 20. Same conditions except load. Upper record—field amperes—positive values zero line—wavy field current line indicates that motor is hunting slightly. Middle record motor voltage. Lower record armature amperes.



[NEWBURY]

FIG. 25—APPLICATION OF LINE VOLTAGE WITH OPEN FIELD CIRCUIT. ⅔ STARTING VOLTAGE—NO EXTERNAL LOAD—200-KV-A. MOTOR

Compare with Fig. 20. Same conditions except open field circuit. Upper record field amperes. (Zero because of open field circuit). Middle record motor voltage. Lower record armature amperes.

[NEWBURY]

FIG. 26—APPLICATION OF LINE VOLTAGE WITH OPEN FIELD CIRCUIT. ⅔ STARTING VOLTAGE. 70 K.W. LOAD ON 200-KV-A. MOTOR

Compare with Fig. 22—same conditions except open field circuit.

The oscillograms taken do not show zero voltage during the interval the line switch is open because the counter e.m.f. of the motor is recorded. Since, during this interval, the motor is not connected to the supply circuit, the counter e.m.f. will follow the field excitation alone rather than the combined magnetizing effect of the field and armature currents; thus in the oscillograms representing excess field excitation the counter e.m.f. of the motor will increase (see Fig. 15, 18 and 21), and in oscillograms representing the under-excited condition the counter e.m.f. of the motor will decrease (see Figs. 17, 20 and 22).

When the switch is closed, applying the higher voltage to the motor, there is a momentary rush of current which may either decrease to a minimum value and then gradually increase to the steady value, or may gradually decrease to the steady value. At the instant of application of the higher voltage, the field current decreases and then steadily increases to its original direct-current value.

The reason for these relative changes in voltage and current will be clear when it is remembered that the field winding constitutes a closed circuit in inductive relation with the armature circuit, and currents will flow in this circuit in a direction to oppose any change in the flux through the circuit. Thus when the armature voltage is changed, requiring a proportional change in flux, the induced current in the field circuit will decrease the existing current if the flux is increased, and will increase the existing current if the flux is decreased. This is true whether the existing field current is more or less than required for unity power factor. The relative changes in field and armature current when the switch is opened may be similarly explained. If the motor is over-excited, as in Figs. 15 and 18, the existing armature current has a large demagnetizing component. When this is removed by opening the switch, the flux tends to increase so that the current in the field winding decreases. On the other hand, if the motor is under-excited, the out-of-phase component of the armature current is magnetizing and when this is interrupted the flux is decreased and the field current is increased.

In the operation of synchronous motors, it has been noticed that the current rush in changing from the starting voltage to the running voltage, the motor being in synchronism on the low voltage, is much larger with small field excitation than with large field excitation. In some cases the current taken by the motor with small field excitation has been sufficient to open the circuit

breakers or damage the starting equipment. Various theories have been advanced for this observed fact, most of them involving the different phase relations existing with different excitations. The series of tests under discussion, however, show that this factor has little, if any, effect on the current taken by the motor under the operating conditions imposed, and that the real explanation is very simple. It will be noticed in Figs. 15, 18 and 21, showing the action with maximum field excitation, that the counter e.m.f. of the motor during the interval that the switch is open, increases to meet the higher voltage applied when the switch is closed. In Figs. 17, 20 and 22, illustrating the action with zero excitation, the opposite effect on the counter e.m.f. is observed, the counter e.m.f. falling as soon as the switch is opened. Due to this behavior of the counter e.m.f., there exists only a small difference between the counter e.m.f. of the motor and the high line voltage at the instant the switch is closed when the motor is over-excited, and there exists a large difference when the motor is over-excited. To check this point quantitatively, the maximum voltage difference at the instant of closing the switch and the maximum current rush were measured on about 20 oscillograms and the results plotted in Fig. 23. This curve shows an approximate proportional relation between the increase in current and increase in voltage, irrespective of the difference between applied starting voltage and applied normal line voltage, and irrespective of the load on the motor, up to the value of load used in the tests.

Whenever the phase relation between current and voltage is changed, as, for example, when the voltage is changed with constant excitation, there is a corresponding change in space relation between the rotor and the magnetic field established by the stator, which requires a change in torque and current to accomplish it. The fact that the load upon the motor does not affect the current rush shows that this factor does not have a controlling effect on the current taken by the motor. Again, the rotor will slow down during the interval the armature circuit is open, which may increase or diminish the required change in rotor position. This also has had very little, if any, effect on the current in the tests made, but the interval between opening and closing the switch is very short, less than two cycles, and with a longer interval this factor might easily become the controlling one. Later on, oscillograms will be shown (Figs. 27 to 30) illustrating the action with larger loads, and the effect of phase position will be found to be of controlling importance.

The relation between the maximum armature current at the instant of change in voltage and the field excitation is shown in Fig. 24 for two starting voltages and with no external load on the motor. These curves have been drawn in such form that they represent the familiar *V* curves of synchronous motors with the addition of the maximum instantaneous current curves. This maximum current curve shows graphically the large increase in maximum current with small field excitation. From these curves the armature currents for the various stages of the starting operation can be obtained for any value of field excitation;

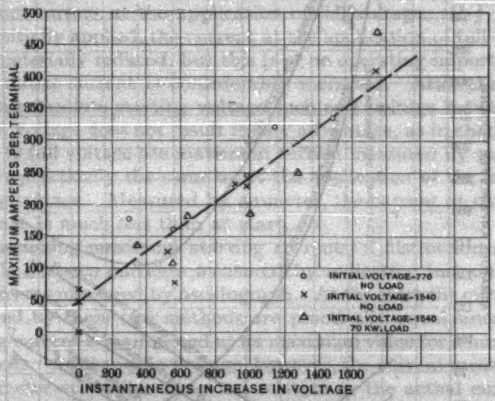


FIG. 23—RELATION BETWEEN INSTANTANEOUS CHANGE IN VOLTAGE AND CURRENT FOR THREE STARTING CONDITIONS. 200-KV-A. MOTOR

for example, with 40 amperes field excitation the motor will take a steady current of 125 amperes (curve *A*) on ½ starting voltage. In throwing over to normal voltage, the maximum current will be 162 amperes (curve *B*) and will settle to a steady value of 57 amperes (curve *C*). Similarly, when starting on ¾ voltage instead of ½, and with the same excitation, the motor will take a steady current of 95 amperes (curve *D*) which will decrease to the value of 46 amperes (curve *E*) when thrown on full voltage and will then increase slightly to 57 amperes (curve *C*) as the steady running value. The initial starting currents (not shown in Fig. 24) are 159 amperes at ½ voltage and 328 amperes

at $\frac{3}{4}$ voltage. Fig. 24 illustrates the major importance of field excitation in reducing the maximum instantaneous armature current when the voltage is changed from the low to a high value. As a matter of fact, the field excitation may have a greater effect on the maximum armature current than the difference between starting and running voltages. It is usually considered of ad-

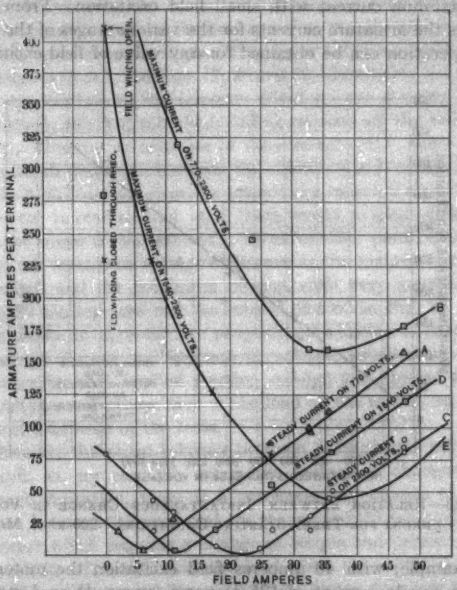


FIG. 24—RELATION BETWEEN ARMATURE CURRENTS AND FIELD CURRENTS— NO EXTERNAL LOAD—200-KV-A. MOTOR

vantage, in reducing the maximum current, to use two starting voltages instead of one; that is, starting on $\frac{1}{3}$ voltage, changing to $\frac{3}{4}$ voltage and then applying full voltage instead of applying full voltage immediately after starting on $\frac{1}{3}$ voltage. Fig. 24 shows, however, that with two starting voltages and low excitation the current rush may be greater than with one starting

voltage and high excitation. At 1540 volts and 10 *amperes*, field excitation, the steady current is 6 amperes, which increases to 200 amperes when 2300 volts are applied. On the other hand, at 770 volts and 35 *amperes* field excitation, the steady current is 106 amperes which increases to 160 amperes when 2300 volts are applied.

For the complete starting operation, the minimum starting current is obtained by starting on $\frac{1}{3}$ voltage and throwing over to full voltage after synchronism has been attained and maximum excitation has been applied. Under these circumstances, the maximum current at standstill is approximately equal to th$ maximum current at the application of full voltage. If $\frac{2}{3}$ voltage is initially applied, the current at the application of full voltage is materially reduced, but this is of no operating importance as the initial current is considerably increased. Also, the use of an intermediate starting voltage such as $\frac{2}{3}$ voltage between $\frac{1}{3}$ and full voltage does not result in any advantage, as in changing from $\frac{1}{3}$ to full voltage the maximum current measured by oscillograph is practically the same as at the application of the initial starting voltage. Measured by ammeter, the current at change in voltage is much less than at start.

In discussing maximum starting currents, a distinction must be made between currents measured by indicating instruments and currents measured by oscillograph. At the start the currents measured by these two methods are practically equal since the starting current is maintained at its maximum value for a number of seconds. At change in voltage, however, the current measured by ammeter very often bears no relation to the actual current measured by oscillogram since the maximum current may exist for only a few alterations.

There is one more point of interest in connection with maximum current at change in voltage which may be mentioned. Fig. 20 shows the condition with zero excitation and closed field circuit. Fig. 25 shows exactly the same conditions except that the field circuit is open. Similarly, Fig. 22 shows the same conditions as Fig. 20 except that the motor is carrying an external load. Fig. 26 shows the same conditions as Fig. 22, except that the field is open-circuited instead of short-circuited. A comparison of these oscillograms shows a marked increase in current rush with open field circuit. This is satisfactorily explained by the restraining effect of the induced field current, in the case of the closed field circuit, on any change in flux.

IV—Motor Running on Partial Load with Field Short-Circuited with External Load but not in Synchronism; Field then Excited and Synchronism Attained; Full Voltage then Applied

In the cases previously considered, the motor is in synchronism on the initial starting voltage and without excitation. Under these conditions the maximum load the 200-kv-a. motor would carry is 70 kw. Obviously, larger loads can be pulled into synchronism by exciting the motor before synchronism is attained and depending upon the excitation to pull the motor into synchronism. Unfortunately, tests under these conditions could not be made with the same motor that was used for the previous oscillograph tests. The two motors, however, are of such similar design that the loads carried, considered as a percentage of the motor normal rating, may be fairly compared. The 70 kw. carried by the 200-kv-a. motor without excitation represents 35 per cent of the normal rated torque of the motor. The 150-kv-a. motor synchronized a load of 90 kw., or 60 per cent of its normal rating with maximum excitation. The load was obtained by belting a direct current generator to the synchronous motor and loading the generator on resistance. The load varies approximately with the square of the speed (with constant resistance), the loads referred to being the maximum load at synchronous speed. This condition is illustrated in Fig. 27. The oscillogram clearly shows how the phase position of the rotor with respect to the armature current and flux is changed by the application of field excitation. During the interval that the line switch is open, the motor evidently falls behind with respect to the phase of the line voltage to such an extent that on closing the switch the motor is not in synchronism with consequent abnormal increase in armature current and variation in field current. Under this condition of load, therefore, the same simple relation between instantaneous increase in applied voltage and resulting current, as shown in Fig. 23, does not hold. In Fig. 27, with practically zero instantaneous increase in voltage the maximum current is approximately 200 amperes. In Fig. 29, with 1800 volts increase, the maximum current is only 150 amperes.

V—Motor Running on Partial Voltage with External Load Excited but not in Synchronism; Full Voltage then Applied and Synchronism Attained

Still larger loads can be synchronized if the final voltage is depended on to pull the motor into synchronism. It was found

by experiment that a load of 139 kw. could be synchronized in this manner. This load is equal to 92 per cent of the motor rating. On successive trials, loads of 139 kw., 133 kw. and 123 kw. were synchronized. Further increase in the load was limited by the assumed heating limit of the motor windings. The tested loads, therefore, do not represent the maximum loads that can be synchronized without regard to other limits. These results were obtained with a field current of 15 amperes which is somewhat less than the current required for normal voltage on open circuit. Oscillograms illustrating this condition are shown in Figs. 28 and 29. All conditions in the two oscillograms are the same except the loads carried by the motor. In Fig. 28, the load is 112 kw., and in Fig. 29, 139 kw. In both oscillograms it will be noticed that during the time the motor is excited on low voltage, and is not in synchronism, the maximum armature current on each successive swing is slightly greater. This indicates that the condition is unstable and if continued long enough the motor will swing far enough from its proper phase position to lose its torque and stop.

In Fig. 30 is shown an oscillogram for the same conditions except that the excitation is increased to 35 amperes, the field current resulting from 125 volts on the field without the rheostat. The load at synchronous speed is 110 kw. Comparing Fig. 30 with Figs. 28 and 29, it will be noted that the increased excitation is detrimental. The armature current when the field is excited is much larger and the current increases more on successive swings. The armature current and field current are greatly increased on increase in voltage to normal, and it requires a longer time (six complete oscillations instead of three) for the rotor to drop into exact synchronism.

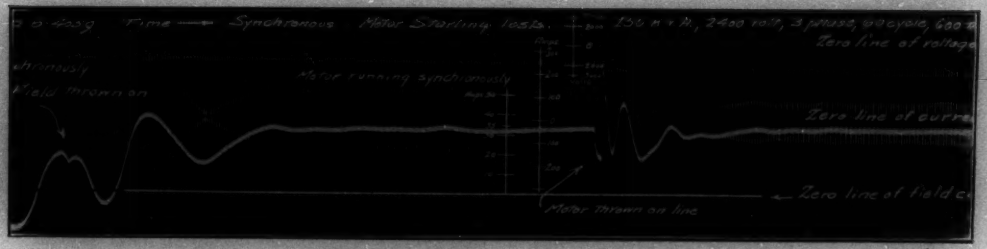
The probable reason for the better performance with under-excitation is the more advantageous initial position of the rotor (with respect to the line voltage). With under-excitation the rotor is ahead of the field due to the line voltage and with over-excitation the rotor is behind. Consequently, when the line voltage is removed and the rotor drops back due to the braking action of the load, it is not so far out of phase with under-excitation as with over-excitation. This explanation can only apply when the rotor is in synchronism on the low voltage as in Fig. 27. When the motor is not in synchronism on the low voltage, the phase position at the instant of change in voltage is not determined by the excitation, but by chance.

The complete statement of the effect of excitation on armature current when line voltage is applied, therefore, becomes:

With motor loads such that the motor is in synchronism before the application of line voltage and does not greatly fall back during the interval the line switch is open, the maximum current is proportional to the instantaneous increase in voltage and over-excitation is the most favorable condition. When, however, the motor is heavily loaded so that the motor is not in synchronism before the application of line voltage *or* does greatly fall back during the interval the line switch is open, the maximum current depends on the extent to which the rotor is out of phase at the instant of line voltage application, and under-excitation is generally the most favorable condition.

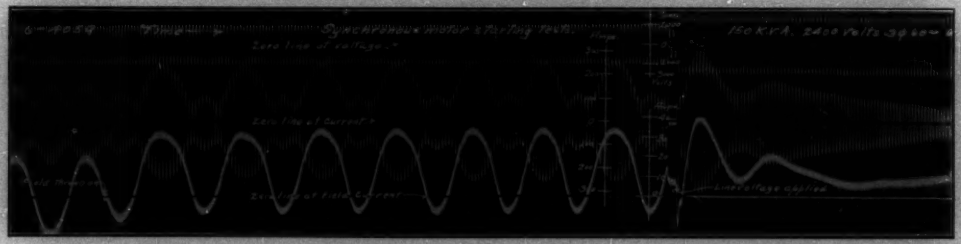
In practise the motor is usually in synchronism on the starting voltage, so that in the majority of cases over-excitation is the best condition.

It will be noted from the oscillograms that these large loads have been started and synchronized at the expense of excessive line currents. The maximum current amounts to 6.5 times the rated current of the motor with under-excitation and to 9 times with over-excitation. This large current is not objectionable, providing the motor rating is small compared with the generator capacity supplying it, and providing the motor winding and starting equipment have been designed with these large currents in view. It should also be borne in mind that the motor tested was not designed specifically for this service. This value of starting current could be materially reduced by modification of the design of the motor to approach more closely the usual design of an induction motor and by the use of reactance in the starting circuit. It will be noted that if the starting current is reduced by the insertion of reactance as an intermediate step between starting and line voltage, it will be necessary to reduce the current rush on application of excitation, if any material reduction in current is to be obtained, as the latter current is nearly as large as the current rush on application of line voltage. This, obviously, can be done by delaying excitation until the motor is running in synchronism on line voltage. While this method of starting and synchronizing was not tried with the 150-kv-a. motor used for the oscillograms shown, it has been tried with other motors and found successful. With a 200-kv-a. 6600-volt, 25-cycle 500-rev. per min. motor designed to drive a mine fan, the fan load amounting to 200 h.p. (represented on



[NEWBURY]

FIG. 27—MOTOR SYNCHRONIZED ON APPLICATION OF EXCITING CURRENT. ¼ STARTING VOLTAGE—35 AMPERES FIELD CURRENT. 88.7 KW. LOAD ON 150-KV-A. MOTOR



[NEWBURY]

FIG. 28—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE. ¼ STARTING VOLTAGE—15 AMPERES FIELD CURRENT. 139 KW. LOAD ON 150-KV-A. MOTOR

Original oscillogram was continued for ten seconds beyond the printed oscillogram so that there is no doubt that motor maintained synchronism.

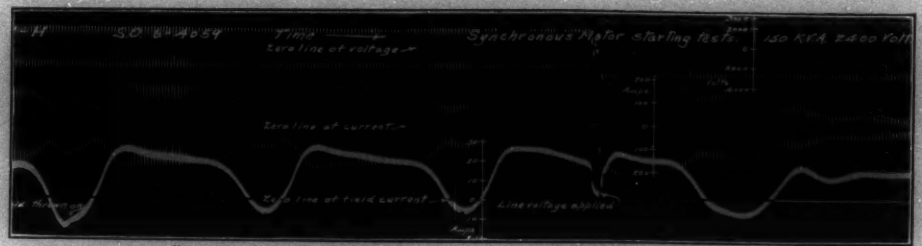
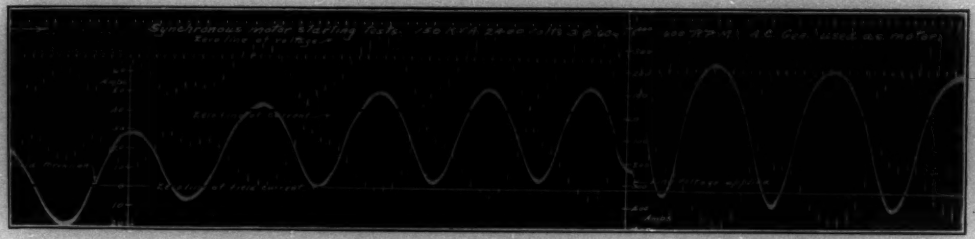


FIG. 29—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE [NEWBURY]

Same conditions as Fig. 28 except load is 112 kw.



[NEWBURY]

FIG. 30—MOTOR SYNCHRONIZED ON APPLICATION OF LINE VOLTAGE. ‖ STARTING VOLTAGE — 35 AMPERES FIELD CURRENT 110 KW. LOAD ON 150-KV-A. MOTOR

FIG. 30—(*Continued*)

PLATE XXXIII
A. I. E. E.
VOL. XXXII, 1913

test by a loaded d-c. generator) was started and synchronized with a maximum line current (measured by oscillograph) equal to 2.44 times the rated current of the motor. Without the reactance the current rush on changing from the starting voltage of 5000 volts to line voltage of 6600 was sufficient to trip the circuit breakers. While the current was not measured, the reactance clearly caused a large reduction in current.

The main facts in regard to synchronous motor starting as discussed in this paper form only a small part of the story that the oscillograms might tell, as the result of a complete and detailed analysis. The study the author has been able to give them has been, to the author, both interesting and profitable and independent study by other engineers will, it is felt, be well worth while.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

COMMUTATING-POLE SATURATION IN D-C. MACHINES

BY HAROLD E. STOKES

The saturation of the commutating pole is one of the principal factors upon which depends the satisfactory operation of d-c. commutating-pole machines. This is especially the case in such classes of machines as d-c. rolling mill motors, railway generators and other d-c. machines having to withstand heavy momentary overloads. Owing to the difficulty of measuring the fluxes combining to produce saturation, under normal working conditions, by other than sensitive laboratory tests, the designing engineer's knowledge of the phenomena attending the commutating-pole fluxes has lagged somewhat behind their application in commercial practise.

Tests have been made at various times, by different engineers, to ascertain the saturation of commutating poles, and as far as the author knows, a method of test employing the ballistic galvanometer has always been used. This is necessarily a test involving considerable refinement and can scarcely be considered a commercial test floor method. Hence, most designers have been satisfied with obtaining sparkless commutation, or if brush potentials gave them an approximate indication of the working saturation of the commutating pole.

A method of obtaining iron saturations and losses has been used by Dr. Gisbert Kapp for transformers and other stationary apparatus, which consists in varying the flux density by changing the excitation, and observing the time of change, the exciting ampere-turns and the voltage induced in an auxiliary coil enclosing the iron section carrying the fluxes to be investigated. This method has been adapted by the author for the

purpose of obtaining commutating pole saturations under normal working conditions. Satisfactory results have been obtained and owing to the method being devoid of the extreme refinement necessary to secure good results by the ballistic method, can frequently be employed by the ordinary test floor staff.

The machine to be tested has the armature fixed to prevent movement and the various windings—armature, series, shunt coils and commutating pole coils—connected for operation as a motor. The shunt coils are excited to their normal value of current. A coil consisting of a few turns of flexible wire is wound around the commutating pole at the point to be investigated, and the ends connected to a millivoltmeter.

By varying the current flowing through the commutating pole coils, a deflection is obtained on the millivoltmeter due to the varying flux at the part of the commutating pole embraced by the coil. By suitably varying the current through the machine so as to obtain an almost constant deflection on the millivoltmeter, observations of main current, millivoltmeter deflection and time in seconds, can be made. From these observations, the saturation of the commutating-pole at various loads and under working conditions can be calculated.

The determination of the best number of turns and resistance to be used in the exploring coil and the method of calculation are as follows:

$$e = T\frac{dN}{dt}10^{-8} = TA\frac{dB}{dt}\cdot 10^{-8}$$

and

$$10^8\frac{e}{TA} = \frac{dB}{dt}$$

Integrating, we have

$$\int_0^t 10^8\frac{e}{TA}\,dt = \int_0^B dB$$

$$\frac{e}{TA}t\,10^8 = B, \text{ and } t = \frac{BTA}{e\,10^8}$$

$$e = \frac{BTA}{t\,10^8}$$

Where e = Volts induced in exploring coil
T = Number of turns in exploring coil.
A = Cross-section area of commutating pole.
N = Flux linking exploring coil.
t = Time in seconds.
B = Flux density in commutating pole.

The approximate commutating-pole flux entering the armature is known to the designer and is of a dimension, say 500,000 c. g. s. lines. The commutating-pole section is say 100 sq. cm., giving $B = 5000$. A time of about 25 seconds is necessary to vary the main current from zero to the maximum value and obtain the necessary readings. A reading of two millivolts is assumed and the number of turns in exploring coil follows from the above formulas:

$$0.002 = T \times 100 \frac{5000}{25} \times 10^{-8}$$

$$T = \frac{0.002 \times 25 \times 10^{8}}{100 \times 5000} = 10$$

The resistance of the coil should be low enough so as not to absorb a large proportion of the induced volts in the exploring coil. The actual volts induced

$$e = \text{millivoltmeter reading multiplied by } \frac{\text{resistance of millivoltmeter} + \text{resistance of exploring coil}}{\text{resistance of millivoltmeter.}} \quad (1)$$

Generally speaking, if the resistance of the exploring coil does not exceed about 0.2 to 0.3 ohms, while the resistance of a millivoltmeter reading 10 millivolts full scale reading, is 1.0 ohm, satisfactory results will be obtained even on small machines with a commutating-pole flux of small dimensions.

Formula (1) is based on a constant $\frac{\text{change of flux}}{\text{change of time}}$ giving a constant induced voltage in coil, but as in practise it is difficult to vary the current in the machine at such a rate as to give a constant change of flux with regard to time, it is sufficient if the current is varied at such a rate as to enable the operator to obtain steady voltage readings, taking periodically every three seconds simultaneous readings of current and time.

Connections are made as in Fig. 1; the shunt coils are separately excited to normal value and a booster capable of giving three or four times full load current is used to supply current to the machine undergoing the test. The current is varied at a suitable rate by means of a rheostat in the booster field, which is separately excited. With the exploring coil around the tip of commutating-pole, starting from zero, increase the current through the machine at a suitable rate; take readings as described above until, as the commutating-pole approaches saturation, the millivoltmeter reading begins to decrease.

At the point where the commutating-pole flux entering the armature reaches a maximum value, the millivoltmeter will be reading zero and any increase in the load current will result in a decrease in the flux entering the armature and threading the exploring coil. This decrease will produce a reverse reading in the millivoltmeter.

A complete set of positive and reverse readings should be taken until the load current is carried as high as conditions will permit. The change of flux can be calculated for each set of readings taken, from formula (1), by substituting time in seconds between each reading and volts obtained on the millivoltmeter. From the summation of the fluxes thus obtained, a saturation curve can be plotted, showing flux and exciting ampere-turns.

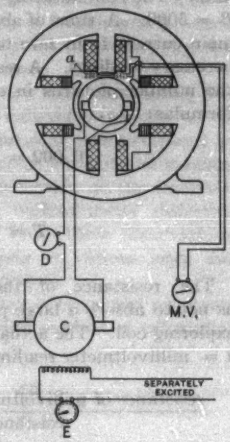


FIG. 1

A. Exploring coil.
M.V. Millivoltmeter, double reading.
C. Booster capable of supplying current to required limit and with field separately excited.
D. Ammeter in series with armature, series and commutating coils.
E. Booster shunt field rheostat.

Fig. 2 shows a saturation curve (*a*) taken at the commutating-pole tip while curve (*b*) shows commutating-pole saturation at the junction with the frame. To obtain curve (*a*), the load current was increased until the direction of the interpole flux entering the armature was reversed at point X, due to the commutating-pole ampere-turns being all absorbed in balancing the armature ampere-turns and in pushing the leakage flux through the commutating-pole. To obtain curve (*b*), the exploring coil

was placed round the commutating-pole as near to the magnet yoke as possible. Readings were taken as for curve (a). The leakage ratio, at any load, is given by $\frac{b-a}{a}$ and is practically constant until the flux approaches the knee of the saturation curve.

While it is of only secondary importance to know the point in the load at which the useful flux becomes zero, it is of great importance to be able to predetermine the useful flux at the maximum overload at which the machine is to operate. Satisfactory commutation at the maximum overloads is dependent on a reasonably accurate predetermination of the useful commutating-pole flux.

Fig. 3 shows the ampere-turns on the commutating-pole available for driving the useful flux into the armature. $O\ B$

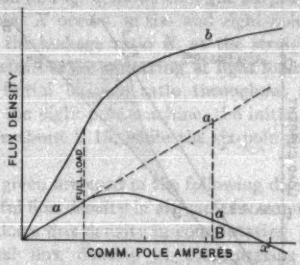


FIG. 2
Curve (a) shows useful commutating pole flux entering armature.
Curve (b) shows commutating pole flux against yoke.

shows commutating-pole ampere-turns plotted against load current.

With a ratio

$$\frac{\text{commutating-pole ampere-turns}}{\text{armature ampere-turns}} = 1.5,$$

$O\ A$ represents armature ampere-turns at any load. The horizontal length between $O\ B$ and $O\ C$ shows the ampere-turns taken to push the useful and leakage flux through the commutating-pole iron; thus, at full load, the iron ampere-turns are almost zero, while at two and one half times full load the iron ampere-turns are represented by $A''\ B''$.

The excess of commutating pole over armature ampere-turns, is given at full load by $D'\ B' - D'\ A' = A'\ B'$, and as the iron ampere turns are negligible, the full amount $A'\ B'$ is available

to push the useful flux into the armature. At two and one half times full load the iron ampere-turns are shown by C'' B'' and are equal to the excess ampere-turns A'' B''. At this point in the load, the ampere-turns required to balance the armature ampere-turns are given by D'' A'', and the excess is all absorbed in pushing leakage flux through the commutating pole, so there is left zero ampere-turns to push useful flux into the armature. At this point, therefore, the useful flux becomes zero, and corresponds to point X in Fig. 2. At loads greater than two and one half times full load, the ampere-turns to push the leakage flux through the commutating pole exceed the excess ampere-turns and there are insufficient ampere-turns to balance the armature; in consequence the direction of the useful flux is reversed.

Fig. 3 is useful in obtaining a clear conception of the forces

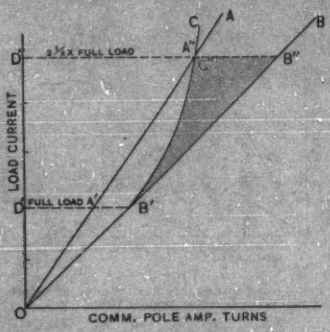


FIG. 3

acting at various loads to produce the useful flux for commutation; the length A' B' may be considered as representing reactance volts at full load due to the reversal of the current in the armature coils undergoing commutation. The shaded area shows, at any load, the uncompensated reactance volts, and this figure should not exceed the permissible value for successful operation at the maximum overload at which the machine is to operate.

Tests made on machines of different characteristics show a wide difference in the point X (Fig. 2) at which load current the reversal of the useful commutating-pole flux takes place. An eight-pole generator designed for normal overload capacity showed the reversal point X occurring at about four times full load current, while a six-pole machine showed the useful flux to

be still about 70 per cent of its maximum value at a load of five times full load; the reversal point X would probably not occur until a load current of 10 to 12 times full load current was reached.

In Fig. 2, the dotted line $a\,a'$, drawn through the straight part of curve (a), the useful flux, represents, in its ordinates, the reactance volts at any load, thus $a'\,B - a\,B$ gives the uncompensated reactance volts, to a certain scale, corresponding to the load b. It is therefore important that the actual curve $a\,a$ should lie along the straight line $a\,a'$ within the limits of operation of the machine. The part $a'\,a$, representing the dimension of uncompensated reactance volts, should not be greater than experience shows to be the maximum for reasonably sparkless commutation.

A consideration of Fig. 2 shows that the surprising difference at which the point X occurs, in six- and eight-pole machines, is due mainly to the leakage ratio R, at the straight part of the leakage and useful curves occurring at light loads. This ratio is termed the initial leakage ratio throughout the following discussion. In the eight-pole machine, the initial leakage ratio was found to be about 2.15, while the six-pole machine gave a figure of 1.0.

The symbols given are used in the following discussion.

B_u = Useful flux density in air gap of commutating pole.

B_l = Leakage flux density in commutating pole at yoke.

B_t = Total flux density in commutating pole at yoke $= B_u + B_l$

K_u = Coefficient of useful flux = gap length $\times$ 0.8 $\times$ gap. coefficient.

K_l = Coefficient of leakage flux = effective leakage gap length $\times$ 0.8.

$A.\,T.$ = Ampere-turns.

$A.\,T_e$ = Total ampere-turns on commutating pole minus armature ampere-turns

$A.\,T_s$ = Ampere turns for pushing leakage flux across effective leakage space.

$A.\,T_t$ = Total commutating pole ampere-turns.

$A.\,T_i$ = Total iron ampere turns for useful and leakage flux.

$$R_l = \frac{A\,T_t}{A\,T_e}$$

$$= \frac{\text{Total commutating pole ampere-turns}}{\text{Total commutating pole ampere turns} - \text{armature ampere turns}}$$

Fig. 2 shows that until some degree of saturation is reached in the commutating pole, the curves showing the useful and total flux are straight line curves, and hence the leakage flux, *i.e.*, total flux minus useful flux, is also a straight line curve for so long as the total and useful curves are straight. It is therefore evident that the leakage gap can be represented by a certain definite equivalent gap length with the total ampere-turns as effective over that gap length. The above symbol K_l is thus obtained:

$$A.\,T_a = B_l \times K_l, \text{ and } K_l = \frac{A.\,T_a}{B_l}$$

For the purpose of this discussion, it is assumed that the commutating-pole is of uniform section from tip to junction with the yoke and therefore B_u in gap will also be of the same dimension as B_u in the pole.

$$A.\,T_i = K_l\,B_l + A\,T_i$$

and

$$A.\,T_i = K_u\,B_u + A\,T_i = \frac{A.\,T_i}{R_l}$$

substituting for $A\,T_i$, and

$$\frac{K_l\,B_l + A\,T_i}{R_l} = K_u\,B_u + A\,T_i$$

$$K_l\,B_l + A\,T_i = R_l\,K_u\,B_u + R_l\,A\,T_i, \text{ and } B_l = B_i - B_u$$

Therefore

$$K_l\,B_i - K_l\,B_u = R_i\,K_u\,B_u + R_l\,A\,T_i - A\,T_i$$
$$K_l\,B_u + R_i\,K_u\,B_u = K_l\,B_i - R_l\,A\,T_i + A\,T_i$$
$$B_u\,(K_l + R_i\,K_u) = K_l\,B_i - A\,T_i\,(R_l - 1)$$

$$B_u = \frac{K_l\,B_i - A\,T_i\,(R_l - 1)}{K_l + R_l\,K_u} \tag{1}$$

With known values of K_l, K_u and R_l, the formula becomes simply

$$B_u = (X)\,B_i - (Y)\,A\,T_i$$

By assuming a series of values for B_i, the corresponding values

of B_u can be directly determined. The values of load current corresponding to values of B_u can then be obtained.

$$A\,T_a = B_l \times K_l$$

where

$$B_l = B_i - B_u$$

$$A\,T_i = A\,T_i + A\,T_a$$

$$\text{and load current} = \frac{A\,T_i}{\text{commutating-pole turns.}}$$

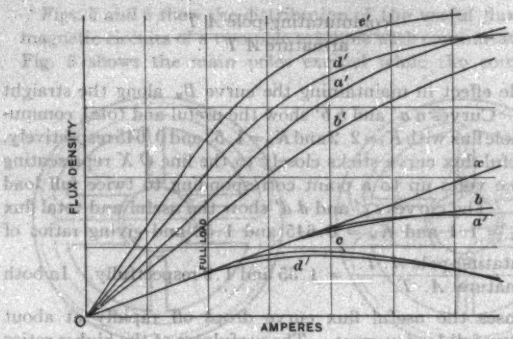


FIG. 4

Curves $a\,a'$.....$Kl = 2.2$, $Ku = 1.53$, $\dfrac{\text{Comm. pole } A.\,T.}{\text{Armature } A.\,T.} = 1.9$

Curves $b\,b'$.....$Kl = 2.2$, $Ku = 0.645$, $\dfrac{\text{Comm. pole } A.\,T.}{\text{Armature } A.\,T.} = 1.35$

Curves $c\,c'$.....$Kl = 1.1$ $Ku = 1.53$, $\dfrac{\text{Comm. pole } A.\,T.}{\text{Armature } A.\,T.} = 1.9$

Curves $d\,d'$.....$Kl = 1.1$, $Ku = 0.645$, $\dfrac{\text{Comm. pole } A.\,T.}{\text{Armature } A.\,T.} = 1.35$

From the machines tested, the values of R_l, K_u and K_l were obtained. These values were substituted in formula (1) and values of B_u and B_i obtained and plotted against the load current. The tested and calculated values of B_u agreed pretty closely. In making the calculation, the $A\,T_i$ were taken for a uniform density along the full length of pole, and even with this approximation, the calculated B_u did not differ more than 13 per cent from the tested figure up to a load of about four times full load current.

Fig. 4 shows a series of calculated curves plotted for the eight-pole machine tested, with varying values of initial ratio, R_i, K_l and K_u. From these curves it is seen that the dimension of K_l is the principal factor in keeping the useful flux B_u along the straight line drawn through the initial useful flux line. Thus if K_l is low, the curve showing B_u will fall away from the straight line representing reactance volts, marked x in Fig. 4, at lower values of load current than for high values of K_l. These curves also show that R_i, or stated in another way, the ratio

$$\frac{\text{commutating-pole } A\ T}{\text{armature } A\ T}$$

has little effect in maintaining the curve B_u along the straight line x. Curves $a\,a'$ and $b\,b'$ show the useful and total commutating pole flux with $K_l = 2.2$ and $K_u = 1.53$ and 0.645 respectively. The useful flux curve sticks closely to the line $O\,X$ representing reactance volts up to a point corresponding to twice full load current. The curves $c\,c'$ and $d\,d'$ show the useful and total flux with $K_l = 1.1$ and $K_u = 0.645$ and 1.53 and giving ratios of $\frac{\text{commutating-pole } A.\ T.}{\text{armature } A.\ T.} = 1.35$ and 1.9 respectfully. In both these cases the useful flux curve drops off rapidly at about 1.45 times full load current. The usefulness of the higher ratios $\frac{\text{commutating-pole } A.\ T.}{\text{armature } A.\ T.}$ is offset by the increased initial ratio of $\frac{\text{leakage flux}}{\text{useful flux}}$

In using the formula

$$B_u = \frac{K_l B_r - A\ T_i\,(R_i - 1)}{K_l + R_i K_u}$$

to ascertain the commutating characteristics of a new design at the maximum operating loads, it is necessary to obtain the values of K_u and K_l; the former may be readily figured as given above, $K_u = l_g \times 0.8 \times K_g$

Where l_g = commutating-pole gap length in cm.

K_g = gap coefficient as obtained by Carter's or Arnold's method.

To determine the dimension of K_1, a consideration of the paths taken by the commutating-pole and main pole leakage and their dependence on the relative magnetomotive forces producing them, is necessary. It has been shown* that the useful armature fluxes due to the main and commutating-poles in any part of the iron circuit, are given by the algebraic sums of the values of $\frac{\text{magnetomotive forces}}{\text{reactance}}$ producing the flux in the path under consideration.

Figs. 5 and 6 show the distribution of the useful fluxes in the magnetic circuits of a two-pole machine with commutating poles. Fig. 5 shows the main poles excited while the commutating

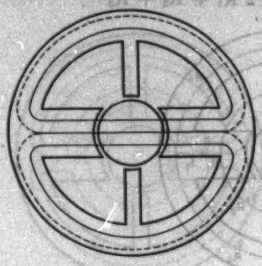


FIG. 5

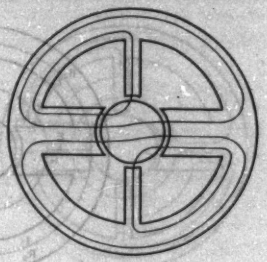


FIG. 6

poles are unexcited. Three lines are shown in the main air gap, a dotted line representing one-half line. Fig. 6 shows the same excitation of the main poles and in addition the commutating poles are excited so that there is one line in the commutating-pole air gap.

These figures show that the part of the frame forming a path common to the main and commutating-pole flux has its flux density increased by one-half of the commutating-pole flux, when the commutating-pole is excited; that part of the frame forming a path not common to the main and commutating-pole flux has the flux density reduced by one half of the commutating-pole flux.

By applying a similar process of reasoning, it can be shown that the main and commutating-pole leakage fluxes follow a distribution closely similar to that of the useful fluxes.

* Brunt in *Electrical Review and Western Electrician*, Sept. 9, 1911, p. 514.

In Fig. 7, the leakage paths of main and commutating poles are shown, the magnetomotive forces being represented by E and e for main and commutating poles respectively. The flux and reluctances of the various paths are represented by I, R and r. Applying Ohm's and Kirchoff's laws, the fluxes in the various paths, with an assumption of a constant reluctance will be as given below.

With only main poles excited

$$I_1 = \frac{2\,E}{2\,R_1 + R_2 + R_3}$$

$$I_2 = I_3 = I_4 = I_5 = \frac{E}{2\,R_1 + R_2 + R_3}$$

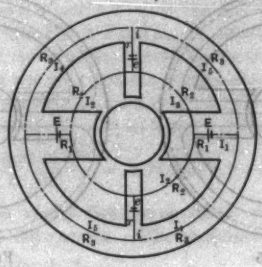


FIG. 7

With only commutating poles excited

$$i = \frac{2\,e}{2\,r + R_2 + R_3} \tag{1}$$

and

$$I_2 = I_3 = I_4 = I_5 = \frac{e}{2\,r + R_2 + R_3} \tag{2}$$

With both main and commutating poles excited.

Since the effect of the two main poles on the commutating poles is to neutralize one another as is also the effect of the two commutating poles in regard to the main poles, then the flux in the commutating poles and main poles will be the same for the same excitation, as for the cases considered with main and com-

mutating poles individually excited without the other. The flux in the leakage paths between poles is given by the following:

$$I_3 = I_4 = \frac{E}{2R_1 + R_2 + R_3} + \frac{e}{2r + R_2 + R_3} \tag{3}$$

$$I_5 = I_6 = \frac{E}{2R_1 + R_2 + R_3} - \frac{e}{2r + R_2 + R_3} \tag{4}$$

A comparison of formulas **1**, **2**, **3** and **4** shows that the leakage flux after the introduction of the commutating-pole excitation, is increased in the paths common to both main and commutating-pole leakage, by one half of the commutating-pole leakage. In the paths not common to both fluxes, the flux is decreased by one-

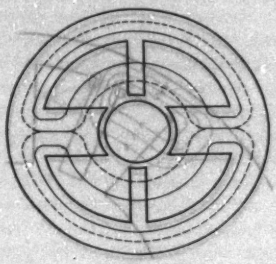


FIG. 8

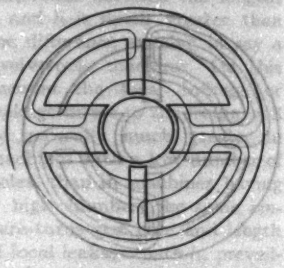


FIG. 9

half the commutating-pole leakage flux. The distribution of the commutating-pole leakage flux is therefore very similar to that of the useful flux.

Figs. 8 and 9 show the distribution of three leakage lines before and after the commutating pole is excited. Compare these with Figs. 5 and 6 showing the distribution of the useful armature flux.

At low saturation, R_1, r and R_3 may be neglected and equations **3** and **4** become

$$I_3 \text{ and } I_4 = \frac{E}{R_2} + \frac{e}{R_2} = \frac{E + e}{R_2}$$

$$I_5 \text{ and } I_6 = \frac{E}{R_2} - \frac{e}{R_2} = \frac{E - e}{R_2}$$

The main pole leakage becomes

$$I_1 = \frac{2E}{R_2}$$

The commutating pole leakage becomes

$$i = \frac{2e}{R_2}$$

At a point in the load where $E = e$, and assuming that the leakage paths of the main and commutating poles have the same reluctance, the leakage is all absorbed by the commutating pole. Fig. 10 represents the leakage flux distribution for this condition. If the machine under consideration is shunt or com-

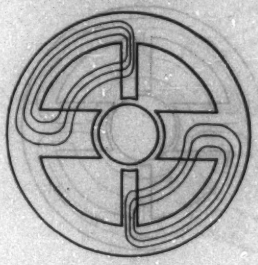


FIG. 10

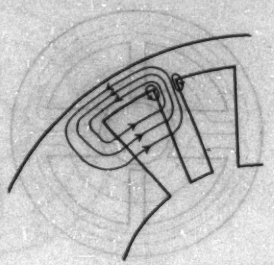


FIG. 11

pound-wound, a further increase in the load current would give $e > E$. As in all normal designs, the total main flux is considerably in excess of the commutating pole fluxes, the distribution of the leakage flux will always be similar to that shown on Fig. 11, *i.e.*, the commutating pole fluxes will take a path through one of the adjacent main poles and will not travel completely round the magnet frame to the next commutating pole. Thus at loads when $e > E$, the commutating pole leakage comprising the excess of commutating pole leakage over main pole leakage must take a local path as shown in Fig. 11.

Some leakage taking a local path, however, exists before the point in the load is reached, at which $e > E$.

Fig. 12 shows a two-pole commutating pole machine, having a mean air leakage path of $2\,l$ or l per pole. The mean leakage path to the frame is l_1.

At a point A in the frame, there will be a leakage due to the left-hand pole, proportional to

$$\frac{A.\ T.}{l_1}, \text{ where } A.\ T. = \text{ampere-turns per pole.}$$

Due to the right-hand pole there will be a leakage to A, proportional to $\frac{A.\ T.}{l_2}$ but in the opposite direction to leakage due to left-hand pole. Hence the actual leakage in path l_1 will be proportional to

$$\frac{A.\ T.}{l_1} - \frac{A.\ T.}{l_2} = A.\ T.\ \frac{l_2 - l_1}{l_1 l_2}$$

In a two-pole machine, the difference between the lengths l_1 and l_2 is much greater than the difference existing in say a twelve-pole machine. On this account the local leakage or leakage direct to the frame, will be generally much greater in machines with a low number of poles, than in machines having a high number, the same ampere-turns per pole and length of local leakage path l_1, prevailing in either case. This effect is, however, more than overbalanced by the decreased length of the path l, and the consequent increase of leakage direct to the pole occurring in machines having a high number of poles.

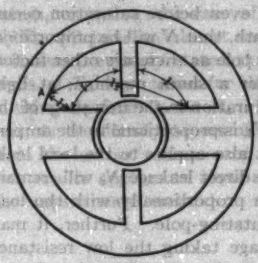


FIG. 12

The local pole leakage will have, in addition to path l, paths l_3 at the ends of the pole, toward the commutator and rear end. This leakage will also be modified by the adjacent pole as described above in connection with the local leakage at the sides.

The local leakage paths should generally be treated separately and summed up into a single expression

$$N_l = \frac{A.\ T.}{l_1}$$

N_l = local leakage per commutating pole.
N_d = direct pole to pole leakage per commutating pole.

N = total leakage = $N_l + N_d$
N_m = direct main pole leakage per pole.
$A.\ T.$ = ampere-turns per commutating-pole.
l_l = mean corrected length of the local paths.
l_d = mean length of direct pole to pole paths.

The direct commutating pole leakage, *i.e.*, pole to pole leakage, may be treated in a similar manner, a number of paths plotted and a resultant expression obtained:

$$N_d = \frac{A.\ T.}{l_d}$$

The total leakage per pole, before saturation is reached, will then be given by the expression, $N = N_l + N_d$.

It does not necessarily follow, even before saturation occurs in the iron parts of the leakage path, that N will be proportional to the $A.\ T.$ of the commutating pole as there are other factors exercising an influence. Consider a shunt machine; at light loads $e < E$, and, assuming no saturation in the iron parts of the leakage path, the direct leakage N_d, is proportional to the ampere turns on the pole; this statement also applies to the local leakage N_l. At load where $e > E$ the direct leakage N_d will remain stationary while N_l will increase proportionally with the load and ampere turns on the commutating-pole. Further, it may happen that the main pole leakage taking the low resistance path through the commutating-pole, has the effect of producing some degree of saturation in the commutating pole. In cases of normally designed machines, it does not seem that this factor has much influence, however.

From the above it is seen that there may be two different dimensions of initial leakage, the earlier one, in point of load, being given by the expression

$$N = \frac{A\ T}{l_l} + \frac{A\ T}{l_d}$$

The second dimension occurring after a point in the load has been reached where the commutating pole leakage is greater than the main pole leakage, will be given by

$$N = \frac{A\ T}{l_l} + \frac{A\ T_b}{l_d}$$

Where $A\ T_b$ = the commutating pole ampere-turns at a load where the direct commutating pole leakage balances the direct main leakage; thus in a shunt machine, the latter part of the formula $\left(\frac{A\ T_b}{l_d}\right)$, will be a constant at all loads higher than that at which the balance between direct main and commutating pole leakage is reached.

To obtain close results when figuring the value of B_u from the formula

$$B_u = \frac{K_l B_l - A\ T_i (R_l - 1)}{K_l + R_l K_u}$$

it is therefore necessary to obtain two values of K_l, one for $N < NM$ and the other for $N > N_m$. K_l will always have two values, excepting the case of a series-wound machine, when N/N_m will have an almost constant relation.

It was previously stated that the commutating pole ampere-turns, $A\ T_i$, were taken for the density at the root of the pole, in using the formula for B_u. This, obviously, is not quite correct, as the density tapers off towards the armature; however, from the author's experience, a comparison of calculated and test results appears to show sufficiently near results to justify the approximate method.

Then $\Delta_1 \Delta_2$ = the commutating pole ampere-turns at a load where the direct commutating pole leakage balances the direct main leakage, that is at short-circuiting, the latter part of the formula $\left(\frac{\Delta_1 \Delta_2}{\Delta}\right)$ will be zero, and all loads higher than that at which the balance between direct main and commutating pole leakage is reached.

To obtain due results when figuring the value of Δ_2 from the formula

$$\Delta_2 = \frac{\Delta_1 \Delta_2 - \Delta \Delta_1 (\Delta_2 - 1)}{\Delta_1 + \Delta_1 \Delta_2}$$

it is therefore necessary to obtain two values of Δ_2, one for $\Delta \geqq \Delta_1 \Delta_2$ and the other for $\Delta \leqq \Delta_1 \Delta_2$, will always have two values, excepting the case of a saturated machine, when $\Delta_1 \Delta_2$ will have an above average value.

It was previously stated that the commutating pole ampere-turns $\Delta_1 \Delta_2$ were taken for the sake of the Δ_2 in the pole in using the formula for Δ_2. This, obviously, is not quite correct, as the density in the pole is actually the resultant of the main and commutating pole ampere-turns, a comparison of calculated and test results shows, however, that this anomaly does result in the approximate method.

From the Δ_2 = 0 it is seen that there must be two different values of Δ for which Δ_2 = 0, which, in turn, means that there are two different values of Δ_1 for which Δ_2 = 0, given by the expression

$$\Delta_1 = \frac{\Delta \Delta_2}{\Delta_2}$$

The normal (underexciting) commutating pole ampere-turns have been reached when the commutating pole leakage is equal to the main pole leakage, and is given by

$$\Delta_1 = \frac{\Delta \Delta_2}{\Delta_2}$$

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

CONSTANT VOLTAGE TRANSMISSION

BY H. B. DWIGHT

For deciding upon the method of operation of a transmission system, two distinct alternatives are presented, one of which has been brought forward but recently. In the older method, which is the one in common use, the voltage of the system is controlled entirely from the generators. The chief disadvantage is the large variation in voltage, which is indeed the factor limiting the carrying capacity of the system. In the newer method, there is no voltage variation at all, this result being obtained by controlling the voltage from both the generating end and the receiving end. The newer method also increases several fold the carrying capacity of a transmission line. This new constant-voltage method has been used successfully in commercial operation, though as yet only on small systems. It offers large advantages both in better service and in lower cost, over the usual varying-voltage method.

It is proposed to make a comparison in the following paragraphs between the two methods, dealing especially with the reduction in cost made possible for large power systems, the reliability of the new method, and the ways in which the new method of operation may influence the design of transmission systems.

The method in common use with transmission lines needs but little description as it consists merely of controlling the voltage on the line by adjusting the voltage of the generators supplying the power. Since at no-load the two ends of the line are at approximately the same voltage, while under load there is considerable drop at the receiver end, a variation in voltage is unavoidable as the load increases or decreases. This variation

may take place at the generator end or the receiver end, as desired, but in either case it puts a limit on the amount of power which the line can transmit. A system which delivers electric power to a customer at a voltage varying 10 or 15 per cent throughout the day is not considered to be giving good service, as the operation of lights and motors is seriously interfered with. Therefore when the load on a transmission system becomes so large as to produce too great a variation in voltage for good service, it has been the customary practise to build additional transmission lines, or to adopt a higher line voltage. It is at this stage that constant-voltage transmission appears most attractive, as it provides greatly increased carrying capacity without any alterations in the transmission line itself.

The constant-voltage method of control is radically different from the usual method. Instead of controlling the voltage from one end only, special machinery consisting generally of synchronous motors or synchronous condensers is installed at the receiver end, and the voltage is controlled at that end also by adjusting the power factor. Enough synchronous motors are installed to keep the voltage at a steady value at both the receiver end and at the generator end.

The way in which the synchronous motors operate to hold the voltage constant is very similar to the way in which they are frequently used to improve the power factor of a load. It is well known that a large part of the voltage drop in a transmission line is due to the line reactance. The reactance drop is greatest when the load has a low power factor, and it is, in fact, directly proportional to the lagging reactive component of the load. The drop is therefore changed into a rise in voltage if the reactive component is leading instead of lagging, and this may be sufficient to overcome the drop due to resistance. This is expressed in symbols as follows:

Let R be the resistance of the line and X the reactance. Let P be the in-phase component of current and Q, the lagging reactive component. Then the drop in voltage is approximately

$$PR + QX$$

or, more exactly,

$$PR + QX + \frac{(PX - QR)^2}{2(E + PR + QX)}$$

where E is the voltage at the receiver.

If now Q is made negative, that is, if it is a leading current, QX opposes the drop PR and tends to neutralize it. The quantity Q can be controlled by adjusting the field current of the synchronous motors, since with a strong field the motors will operate with a leading current. It is therefore possible to control the voltage at the receiver end by adjusting the field current of the synchronous motors. This adjustment must be under the control of the transmission line operators in order to have the correct effect on the line voltage.

In water-power plants the voltage and also the frequency are subject to sudden changes due to variations in load which are too rapid for the waterwheel governors to compensate for immediately. In such cases a large flywheel effect on the system tends to minimize this trouble. Synchronous motors add directly to the flywheel effect and are found very useful in this way.

The advantages obtained from the use of synchronous motors by maintaining constant voltage at both the generator and receiver ends of the line and by adding to the flywheel effect, have been sufficient to warrant their installation on several short transmission systems. In such cases the improvement in the service given to customers at all parts of the system justified the additional expense. But when it is stated that the synchronous motors must be equal to one-half or two thirds of the generator capacity the cost will at first sight seem prohibitive for most cases. In consideration of this, the additional fact must be taken into account that the newer method not only improves the service, but very greatly increases the carrying capacity of the line. Since with a line of about 100 miles (160 km.) in length the cost of the generators is comparatively small compared with the cost of the line, the installation of synchronous motors will actually save money in large systems, by saving extra line construction.

The limit of carrying capacity is ordinarily set by the maximum variation in voltage allowed for good service, that is, by the regulation of the line. But if there is no voltage variation at all, another limit must be looked for, and this will be found in the greatest energy loss which can be allowed for the transmission. Power for supplying line losses costs very little in most systems, so that an efficiency of 85 per cent is generally consistent with good economy. The curves of Figs. 1 and 2 for constant-voltage lines have been plotted for this value of

efficiency. A glance at these curves shows that the carrying capacity of a 25-cycle line can be doubled by adopting the constant-voltage method, and the capacity of a 60-cycle line can be multiplied by two or three.

It is shown in the diagram, Fig. 5, that there is a maximum amount of power for a constant-voltage line, which cannot be exceeded under any conditions without raising the voltage, no matter how low the efficiency is allowed to become, nor how much synchronous machinery is installed. This has been pointed out by Mr. Philip, and a diagram given for the case where

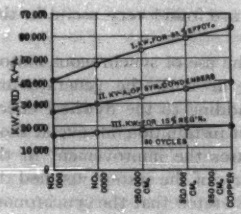


FIG. 1

I. Carrying capacity for transmission lines at constant voltage.

II. Synchronous condensers required.

III. Carrying capacity for transmission lines at varying voltage.

Length of lines, 100 miles. Highest voltage on lines, 115,000 volts. Efficiency and regulation calculated for line alone, without additional reactances.

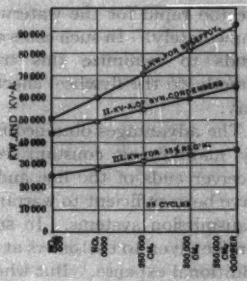


FIG. 2

I. Carrying capacity for transmission lines at constant voltage.

II. Synchronous condensers required.

III. Carrying capacity for transmission lines at varying voltage.

Length of lines, 100 miles. Highest voltage on lines, 115,000 volts. Efficiency and regulation calculated for line alone, without additional reactances.

the receiver voltage is equal to the generator voltage.* The practical limit to the carrying capacity of a line is smaller than the above maximum, due in most cases to the energy loss becoming excessive and to the rapid increase in the amount of synchronous condensers required. The present paper therefore uses as a practical limit a moderate percentage of loss, such as corresponds to about 85 per cent efficiency.

The saving in cost effected by the constant-voltage system increases very rapidly as the number of miles of line becomes

*R. A. Philip, *Economic Limitations to Aggregation of Power Systems.* TRANS. A. I. E. E., 1911, p. 612.

greater. The curves of Fig. 3 show that for 60 cycles, the cost of a constant-voltage line with the necessary synchronous motors represents a saving when the length is over 70 miles (112 km.). For 25 cycles, Fig. 4, the saving over the varying-voltage method is not obtained until the length is 120 miles (193 km.) or more. As noted elsewhere, no allowance has been made for cost of land, owing to the extreme variableness of this item. If this were included, the constant-voltage curves would show more favorably. On the other hand, no allowance has been made for the cost of power for line losses, which are greater for the constant-

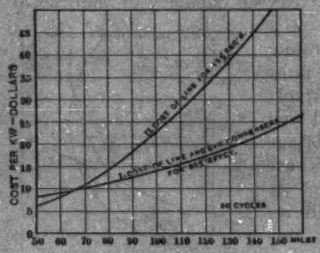


FIG. 3

I. Cost per kw. of transmission line and synchronous condensers, constant voltage.

II. Cost per kw. of transmission line, varying voltage.

250,000 cir. mil copper conductors. 115,000 volts, highest voltage on lines.

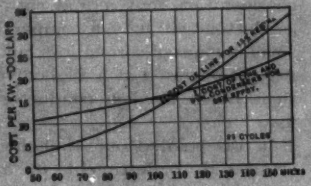


FIG. 4

I. Cost per kw. of transmission line and synchronous condensers, constant voltage.

II. Cost per kw. of transmission line, varying voltage.

250,000 cir. mil copper conductors. 115,000 volts, highest voltage on lines.

voltage lines used in calculating the curves than for the corresponding varying-voltage lines.

The costs as plotted are merely approximate, and are not intended to give an actual estimate of what a transmission line would cost. The curves are presented rather to show the effect on the cost, of changing certain factors such as size of conductors, length of line, and method of control.

The comparisons in Figs. 3 and 4 are not quite complete, owing to another saving in cost which is possible when designing a line for constant-voltage work. This saving is made by using large conductors. The cost curves show that with an existing line of considerable length it pays to install synchronous motors if enough power is to be transmitted to utilize the line to its full

capacity on the new basis. As may be noted from the first two figures, the increase in carrying capacity, and therefore the saving in cost per kilowatt, is greatest when large conductors are used. In ordinary transmission there is practically no advantage in using a larger conductor than about No. 0000 copper for 60 cycles. Reducing the resistance to a value less than one-third of the reactance does not materially improve the regulation, which is determined under these conditions almost entirely by the reactance. But with constant-voltage operation, a large proportion of reactance to resistance within a certain limit is no longer a hindrance, and so large conductors can be used to good advantage. This increases the carrying capacity of the line at small extra cost.

It may be mentioned as a minor consideration that a line with large conductors will have a comparatively small amount of corona loss, and so it may be operated at a higher voltage than where smaller conductors are used.

It was pointed out that high reactance is a detriment to a line operating with varying voltage but is not such a great disadvantage when the constant-voltage method is used. For instance, Figs. 1 and 2 show that a smaller proportion of synchronous motors is needed with a 60-cycle line than with a 25-cycle line. This is due to the higher reactance of the 60-cycle line. Now the reactance used in estimating the curves has been merely the reactance of the line. The reactance of the entire circuit includes that of the generators, step-up transformers, protective reactance coils, and step-down transformers, as well as the line reactance. Of late years it has been customary in large systems to make all these reactances as large as possible for protective reasons, in spite of the fact that they tend to make the regulation poor, and so limit the power which can be transmitted. High reactances give protection by reducing short-circuit currents, which are tremendous in large power stations and are very destructive both in their heating effects and in the mechanical distortions which they produce in the apparatus. High reactance in the reactance coils placed between the line and the station

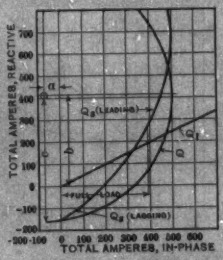


FIG. 5—DIAGRAM, 200-MILE CONSTANT VOLTAGE LINE. CHARGING CURRENT NEGLECTED

apparatus gives very effective protection against abnormal voltages due to lightning, and to surges caused by switching. It is evident that with constant-voltage transmission it will be economical to increase all these reactances much beyond the values in use at present, and better protection will thus be obtained. It may therefore be stated that the possibility of using high reactance in all the various kinds of apparatus connected with the system, is one of the most important points in favor of constant-voltage transmission.

It may safely be stated that the reason why the frequency of 25 cycles was adopted to any extent in this country was because its low reactance made it more economical for transmission. This is shown by the curves of Figs. 3 and 4. The same figures show that with constant voltage, the frequency of 60 cycles becomes as economical as 25 cycles. With the exception of railway work, the frequency of 60 cycles is preferable for most important applications of electric power, especially the supply of power to large cities. The cost of generators, transformers, and motors is generally less at 60 cycles, and the operation of most lighting devices, especially tungsten lamps and arcs, is much more satisfactory at the higher frequency. Any method, therefore, which tends to make 60-cycle transmission more economical than 25-cycle, should be welcomed, as it will assist in standardizing the electric machinery of the country at the single frequency of 60 cycles.

The most advantageous application of constant-voltage transmission is probably not in transmission lines with a single generating station, but rather in large transmission networks connecting all the hydroelectric plants and the cities within a radius of several hundred miles. The generators placed at various points of the network themselves partly take the place of the synchronous motors for maintaining constant voltage, and thus the total capacity of synchronous motors required is somewhat less. Duplicate lines for use as reserves in case of breakdown are not required as much in networks as in straight transmission projects, since power can generally be supplied to any point from more than one direction. Thus a small number of heavy lines can be used in networks, and constant-voltage operation is especially applicable to these. All the advantages of low cost, good service, and good protection which have been described for constant-voltage transmission lines, are to be obtained with a large transmission network operated with steady voltage at both generating and receiving stations.

Very large transmission networks have already grown up, and are steadily increasing in extent. The engineering advantages of combining small power systems into one large network are due to the combination of differing load curves, water storages, reserves in case of breakdown, and even differences in standard time, etc. These have been discussed so thoroughly that they need only be mentioned here. The principles of constant-voltage transmission can greatly increase the economy and range of operation of large transmission networks. It does not seem unreasonable in view of the already rapid growth of many of these systems, to state the possibility of a single high tension network for the supply of power over the entire country.

When larger transmission networks are advocated it might be objected that the limit has been already reached of the number of generating stations which can be connected to one network, owing to the danger from such large amounts of generator capacity when a short circuit occurs. But a network which is operated at constant voltage contains an unusually large proportion of reactance, both in the line and in the station apparatus. Thus when a short circuit occurs the voltage drop toward the short circuit is very rapid. Power is delivered to it practically only from the near-by generating stations of the network.

For example, if a short circuit occurs 100 miles from a station and the voltage is sustained at 100,000 volts, 60 cycles, at the generating station, a current corresponding to only about 100,000 kv-a. will be delivered from the station. This is not such an excessive amount as to interfere with the safe opening of the circuit breakers. The presence of protective reactances very greatly reduces the short-circuit current, so that it may be said that a station 100 miles (160 km.) away from a short circuit cannot send a dangerous amount of current to the short circuit.

The greatest danger, then, comes from a short circuit in the immediate neighborhood of the largest generating station, and in that case the short-circuit current is supplied almost entirely by the nearest station. The largest circuit breakers will therefore not need to be designed with regard to the capacity of the entire network, but only of the stations in which they are located. Circuit breakers are at present in successful operation in connection with as large generating plants as are likely to be constructed and so the problem of handling short circuits will probably not impose a limitation upon the size of transmission networks.

The two systems of varying-voltage control and constant-voltage control have been described as being quite distinct. There is really, however, a middle ground between them. For instance, consider a line operated with 20 per cent voltage variation at the generators between no-load and full load, and with a steady voltage at the receiver. Now by installing a small number of synchronous motors at the receiver, the generators may be operated with only 10 per cent variation, the synchronous motors being used to hold the receiver voltage constant. Twice the number of synchronous motors would allow constant-voltage operation at both generators and receivers. It is possible, therefore, to install a small amount of machinery and obtain a proportionate improvement in closer regulation or in increased carrying capacity of the line.

The above fact is of great importance in relation to the commercial application of the principles of constant voltage operation, since a new method appears much more attractive to a transmission company if the change can be made gradually without interrupting service, and if the results of a small alteration can be observed before investing any large amount of capital.

Many power companies offer special terms to induce their customers to install synchronous motors and thus raise the power factor of the load. This can scarcely be called a step in the direction of using the principles of constant-voltage transmission, since the field current of the synchronous motors is not adjusted with a view toward regulating the line voltage. The advantages of a high power factor of load are very small indeed compared with the large advantages to be obtained from adjustable power factor.

It must not be supposed that the voltage at all points of a constant-voltage transmission line or network has exactly the same value. At all points where there are generators or synchronous motors whose field current can be adjusted, the voltage will be held steady. For the best economy, however, the generator voltage should be held at a higher value than the receiver voltage. Thus the voltage at the generating stations may be held constant at 110,000 volts, while the voltage at the receiver stations may be held steady at 90,000 volts. This involves running the synchronous motors with a weak field and a lagging power factor at no-load, and there is a limit in doing this when the motors are carrying a mechanical load, due to the

danger of the motors dropping out of step. However, the capacity of synchronous motors required is so large that most of them would have to run unloaded as synchronous condensers, since mechanical loads could be found for only a few of them. The curves which have been given assume that the synchronous condensers will operate at their full rating of lagging current at no-load, as well as with leading current at full load.

Synchronous condensers can be designed so as to remain in step, when running unloaded at 100 per cent power factor, as tenaciously as a fully-loaded induction motor. If necessary, the starting torque could be sacrificed for the sake of the synchronizing power, and the condensers could be started by small starting-motors, though it would be preferable to have them self-starting. At times of very light load on the line, such condensers can operate safely with weak fields and lagging power factor. Thus, in spite of the fact that loaded synchronous motors and synchronous converters are commonly regarded, and rightly so, as a very unstable element in transmission line operation, it may be stated that the addition of properly designed unloaded synchronous condensers to a transmission system, as described in this paper, does not decrease the reliability of the system. In fact, the extra reactance which would be used, as described above, renders the line more reliable instead of less so. It may be mentioned that probably more time would be taken in getting load on a line, after a temporary shut-down, where synchronous condensers are installed, but this is not a serious disadvantage if the system is more safe and dependable.

The charging current of the line due to the condenser effect is the same under all conditions of load, and does not affect the amount of machinery necessary for the adjustment of the line voltage as described in this paper. The effect of the charging current is to raise the voltage at the receiver, by a constant amount. The operation of a long constant-voltage line is made more satisfactory by the charging current, but the charging current cannot be considered a help when the line is operated with varying voltage.

It has been found in commercial practise with short lines that constant voltage transmission is worth while merely on account of the improvement in service. In the following paragraphs, estimated costs are given for comparatively long lines, so as to show, even more definitely than by the curves already discussed, that where a line is long, or land is high in value, it

pays to adopt constant-voltage transmission, even without considering the improvement in service.

Summary

Constant voltage transmission requires adjustable power factor.

Advantages.

1. Better service—no variation in voltage.
2. Better protection, due to high reactances.
3. Tendency to use the frequency of 60 cycles.
4. Increased carrying capacity of line. The limit is changed from maximum voltage variation to maximum energy loss. This allows more power to be transmitted or the distance to be increased, without the voltage being raised.
5. Lower total cost for long lines. The saving in cost is greatest for long lines or large networks, large quantities of power, large conductors, and for the frequency of 60 cycles.
6. The method is easy to apply to existing lines. The change can be gradual, and no change is necessary in line construction.

Disadvantages.

1. Cost and attendance of additional rotating machinery.
2. Higher total cost for short lines.
3. In order to obtain the greatest economy from constant-voltage operation, the losses must be increased, and the number of separate lines, which are useful as reserves, must be reduced.
4. Tendency of synchronous machinery to drop out of step, and delay in putting load on the line again after shut-down.

Data Pertaining to Constant Voltage Transmission

Formula for Voltage Drop from Generator to Receiver.—(Neglecting charging current.)

Let E be the voltage at the receiver.

Let I be the current, in total amperes, at a power factor $\cos\theta$ at the receiver end.

Let $P = I \cos\theta$

Let $Q = I \sin\theta$

Let R be the resistance and X the reactance, of one conductor.

COMPARISON OF THE TWO SYSTEMS FOR A 200-MILE TRANSMISSION PROJECT

	The usual varying-voltage method	Constant-voltage method
Distance	200 miles	200 miles
Power delivered	33,000 kw.	33,000 kw.
Power factor of load	90 per cent	90 per cent
Frequency	60 cycles	60 cycles
Number of three-phase circuits	3	1
Conductors, copper cable	No. 0000	350,000 cir. mil.
Maximum voltage on line	116,000	116,000
Voltage at load end	100,000	85,000
Reactive drop in transformers at each end	4 per cent	5 per cent
Reactive drop in protective coils at each end	4 per cent	7 per cent
Synchronous condensers at load end	None	18,000 kv-a.
Synchronous condensers required at no-load		16,500 kv-a.
Voltage variation	21 per cent	None
Voltage variation due to line alone	14 per cent	None
Efficiency of transmission	94 per cent	87 per cent
Power factor at generators	90 per cent lagging	89 per cent lagging
Approximate Costs.		
Towers, ground cables, insulators and erection	$1,140,000	$440,000
Copper cables, at 18 cents lb.	1,080,000	600,000
Synchronous motors and space in substations, at $10.00 per kv-a.		180,000
Cost of line, exclusive of land	$2,220,000	$1,220,000
Saving		1,000,000

N.B. The charging current of the line was allowed for in calculating the above results.

COMPARISON FOR A 100-MILE TRANSMISSION SYSTEM

	Varying-voltage method	Constant-voltage method
Distance	100 miles	100 miles
Power delivered	54,000 kw.	54,000 kw.
Power factor of load	80 per cent	80 per cent
Frequency	60 cycles	60 cycles
Number of three-phase circuits	3	1
Conductors, copper cable	250,000 cir. mil.	400,000 cir. mil.
Maximum voltage on line	113,000	113,000
Voltage at load end	100,000	90,000
Reactive drop in transformers at each end		5 per cent
Reactive drop in protective coils at each end		5 per cent.
Synchronous condensers at load end	None	42,700 kv-a.
Synchronous condensers required at no load		21,500 kv-a.
Regulation due to line alone	15 per cent	None
Efficiency of transmission	95 per cent	91 per cent
Power factor at generators	87 per cent lagging	89 per cent lagging
Approximate costs.		
Towers, ground cables, insulators and erection	$618,000	$227,000
Copper cables at 18 cents per lb.	642,000	343,000
Synchronous condensers and space in sub-stations at $10.00 per kv-a.		427,000
Cost, exclusive of land	$1,260,000	$997,000
Saving		263,000

N.B.: The charging current of the line was allowed for in calculating the above results.

Then the drop in volts for a lagging current =

$$E - \sqrt{(E + PR + QX)^2 + (PX - QR)^2}$$

$$= \text{approximately } PR + QX + \frac{(PX - QR)^2}{2\,(E + PR + QX)}$$

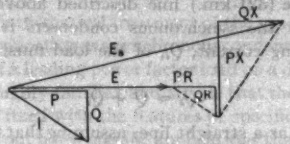
(See Fig. 6a.)

The drop in volts for a leading current is approximately

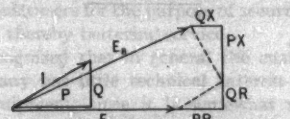
$$PR - QX + \frac{(PX + QR)^2}{2\,(E + PR - QX)}$$

(See Fig. 6b.)

The above approximate forms should not be used when the quantities $(PX - QR)$ or $(PX + QR)$ are greater than about 25 per cent of E. In such cases use the form involving the radical.



(a) LAGGING CURRENT.



(b) LEADING CURRENT.

FIG. 6

DIAGRAM FOR REQUIRED AMOUNT OF LEADING CURRENT

Let the voltage be held at a steady value E at the receiver end of the line, and at a steady value E_s at the supply end of the line. Let Q be a leading current.

Then $E_s^2 = (E + PR - QX)^2 + (PX + QR)^2$

or $(P^2 + Q^2)\,(R^2 + X^2) + 2\,EPR - 2\,EQX = E_s^2 - E^2$

$$\text{That is, } P^2 + Q^2 + \frac{2\,ER}{R^2 + X^2}\,P - \frac{2\,EX}{R^2 + X^2}\,Q = \frac{E_s^2 - E^2}{R^2 + X^2}$$

the charging current being neglected.

This is the equation of a circle, when Q is plotted for different values of P.

Let the center of the circle be (a, b) and the radius c.

Then the circle is $(x - a)^2 + (y - b)^2 = c^2$

or $x^2 + y^2 - 2ax - 2by = c^2 - a^2 - b^2$

Therefore $a = -\dfrac{ER}{R^2 + X^2}$

$$b = +\frac{EX}{R^2 + X^2}$$

and

$$c^2 = \frac{E_s^2 - E^2}{R^2 + X^2} + a^2 + b^2 = \frac{E_s^2}{R^2 + X^2}$$

The circle may now be drawn as in Fig. 5, which is the diagram for the 200-mile (321-km.) line described above. The current Q_s supplied by the synchronous condensers is larger than Q, since the lagging current, Q_l, of the load must be neutralized. That is,

$$Q_s = Q + Q_l$$

Q_l is plotted as a straight line, assuming that the power factor of the load remains constant.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913

Copyright, 1913. By A. I. E. E.

THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS

BY JOHN C. PARKER

The general mathematical treatment of the synchronous motor and its special application as a synchronous condenser—so-called—for the placing of a leading power factor load on a distribution system, is so thoroughly familiar and simple that the present paper will not concern itself with the features of specific analysis. It is desired to point out a few specific applications that may be made, and the means of securing co-operative effort between the central station and its customers for the purpose of securing synchronous motor load and thereby bettering service.

It may be recognized that in general the customer of a distributing company has little technical interest in the use of synchronous equipment, since it is somewhat more expensive than induction motor equipment, does not lend itself readily to extremely small unit installation, and is, even with more modern apparatus, slightly less substantial and easy to operate. On the other hand, on the larger units these difficulties are of less significance, and therefore we may look for industrial applications of synchronous motors where relatively large concentrated power applications occur, possibly supplemented by, but in general differentiated from, group and individual motor drive distributed throughout a manufacturing plant. It will, therefore, be the case that such applications must be made on large centralized equipment, such as air compressors, refrigerating machines, pumps, et cetera, rather than on individual machines, or in those places where the industry depends on one centralized power supply using mechanical distribution throughout the plant; such industries being, for example, the smaller milling

concerns, where all of the manufacturing processes are correlated, giving no diversity factor on the different machines and thereby most readily lending themselves to a mechanical power distribution, all of which operates all of the time when the mill is in commission. Such a mechanical distribution in general offers high efficiency of distribution with a not excessive first cost and maintenance, and with fairly close synchronizing of the different machines driven, so that in such a case individual induction motor installation with electric distribution of power is not economically justified.

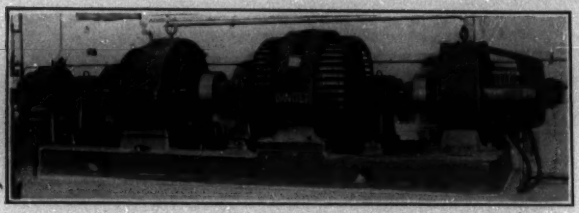
Obviously the synchronous motor in industrial use will not find its place where frequent starting and stopping are required, nor where the starting must be done under full load.

In the cases of relatively large centralized power utilization, the consumer's motive for synchronous motor application is found either in a rate schedule favorable to unity power factor or leading load, in a sharing of the expense of the initial installation by the central station company, or in a special arrangement into which the central station enters for a class rate made lower than the rate offered for induction motor service in consideration of the improvement of distribution conditions, and offered only where such an installation will prove advantageous to the central station company.

Practically all modern systems of charge for electric service are based on the maximum demand in conjunction with the kilowatt-hours, either in the form of a direct charge for power and another direct charge for energy, or on the load factor distributed over a period of time, in which case the charge comes back to either a recorded demand charge or the rating of the connected apparatus. A metered system of demand seems to be distinctly preferable.

By having such a metered demand based on the kilovolt-amperes rather than on the kilowatts, the consumer has a material interest in keeping the power factor as near to unity as possible. This is particularly the case where energy is supplied from a hydroelectric enterprise over a long distance transmission line. In such case a kilovolt-ampere basis of charge is, the writer believes, the rule, and the incentive to the customer to make synchronous installation is a matter of anywhere from ten to thirty per cent of the annual cost of power.

An additional feature, which in the writer's practise is being incorporated into industrial synchronous motor applica-



[PARKER

FIG. 1—SYNCHRONOUS MOTOR-DRIVEN BATTERY CHARGING SET

[PARKER]

FIG. 2—SYNCHRONOUS MOTOR—DRIVEN SET FOR REFRIGERATING MACHINE DRIVE BY VARIABLE VOLTAGE CONTROL

[PARKER]

FIG. 3—6 000,000 GALLON VARIABLE STROKE PUMP DRIVEN BY 600-H.P. SYNCHRONOUS MOTOR

tions, is the use of automatic potential regulators for holding constant voltage at distant points in the transmission line, either with or without inductance inserted in series with the line.

Where the aggregate leading quadrature kilovolt-amperes which it is practicable to get connected to the lines is less than the aggregate lagging quadrature kilovolt-amperes due to induction load, it is manifestly undesirable to insert a series inductance, since the latter would serve to reduce the power factor of the feeder load and maintain a certain minimum potential drop; but even in such a case the synchronous motor with constant potential relay is useful in supplying the leading kilovolt-amperes as the lagging kilovolt-amperes of the induction motor load increase, and vice-versa, thus at all times keeping the condition of the feeder, so far as wattless kilovolt-amperes are concerned, at least as good as the best condition obtaining prior to the installation of the synchronous equipment, and throughout the major part of the day very much better.

Where the synchronous quadrature demand can be made in excess of the lagging quadrature demand from induction motors, it then becomes desirable to put inductance in series with the feeder, thereby overcoming drop due to the in-phase amperes operating in conjunction with the line resistance.

The use of this remote potential control has certain advantages over control by station regulators. First, it combines the two functions of load carrying and of regulation in one piece of apparatus. Second, it is independent of certain approximations in regard to the feeder characteristics; and third, it is independent of the distribution of the load along the feeder at varying hours of the day.

This last factor is of very considerable importance, since a station regulator with a compensator to simulate the line impedance must be arranged for an arbitrarily assumed load distribution, while on most distribution systems in the larger cities, at least, the alternating current feeders traverse a belt of residential territory surrounding the central direct current district, and then pass into the outlying industrial district. Where one set of feeders is maintained for both the residential and industrial districts, the center of load shifts between five and six o'clock p. m. from the industrial load of the outlying districts to the lighting load of the residential districts, and therefore voltage regulator compensation which is carried for one hour of the day is inaccurate for another hour; whereas, with the synchro-

nous motor used as a potential regulator, a motor at all times endeavors to hold strictly constant voltage at the point at which the potential relay is applied to the transmission line.

In view of the fact that such potential regulating relay is only concerned with the voltage delivered to it, a series of such installations may be installed along the length of a feeder with inductances of a simple type inserted into the feeder at points so chosen between the synchronous motor service taps as to have the potential at two adjacent inductances equally high above and below the voltage for which the regulator is set, thereby getting the flattest voltage curve between these inductances and very considerably better regulation over the whole length of the line.

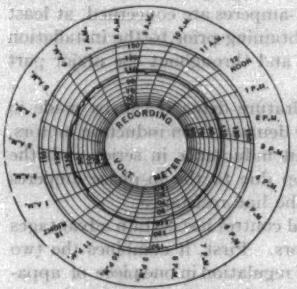


FIG. 4—VOLTAGE AT REFRIGATING PLANT. AUTOMATIC VOLTAGE REGULATOR CUT OUT. SYNCHRONOUS MOTOR OPERATING AT 75 PER CENT LAGGING POWER FACTOR

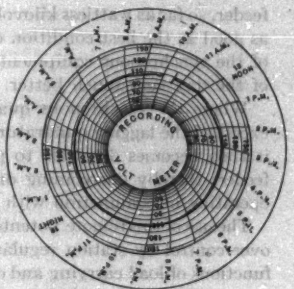


FIG. 5—SAME CIRCUIT WITH AUTOMATIC POTENTIAL REGULATOR IN OPERATION

As the voltage distribution curve along a feeder carrying uniformly distributed load of uniform character is a parabolic function of distance, it is manifest that the segmentation of voltage regulation of such series inductances reduces the variation of potential to a function which is a square of the length of the segments of the line, so that this segmental regulation with but slight multiplication of the segments makes for a material betterment in the conditions throughout the circuit.

It is perhaps hardly necessary to indicate that what we are interested in is primarily leading quadrature kilovolt-amperes, and that these can be got with less and less additional investment

and operating losses as the power factor approaches unity in a machine where power factor correction and shaft load are combined in one motor. This points to the desirability of having connected to the lines as many and as large synchronous motors as may be commercially practicable, rather than combining the power factor correction for a given circuit all in one machine of limited size, or in a synchronous motor used merely for power factor correction.

As to the applications that may be made of the synchronous motor, it may be said that the simplest application is as the driving end of a motor-generator set, where a variable direct-current voltage is desired for such purposes as battery charging in large garages, and speed control of refrigerating apparatus. The illustrations show two such sets, one of 268 kilovolt-amperes

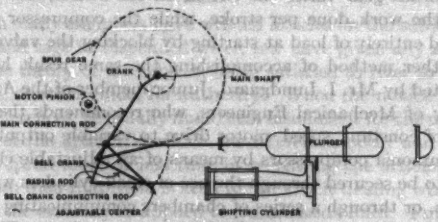


FIG. 6—LINE DIAGRAM OF 6,000,000-GALLON VARIABLE STROKE PUMP (SEE FIG. 3)

capacity at 85 per cent power factor, driving two generators, one of which is used in charging pleasure vehicles and the other for the higher voltage commercial trucks. The other illustration referred to, shows a four-unit set, consisting of a 210-kilovolt-ampere, 70 per cent leading power factor synchronous motor driving a 25-kilowatt constant voltage generator for general power purposes, a small exciter, and a 90-kilowatt direct-current generator, the field excitation of which is varied to supply variable voltage to the armature of the motor operating a refrigerating machine.

A type of application but little used is that in which the driven apparatus itself is adapted to variable output, and to synchronous motor starting. One such case is shown in the illustration of a 6,000,000-gallon pump operated by a 600-horse power, 375-volt synchronous motor. In this case the pump

stroke is made variable by means of a linkage hydraulically operated, whereby the piston stroke may be reduced quite to zero and the no-load torque thereby brought well within the pull-in torque of the motor. After the motor is in operation, the stroke of the pump may be varied at will, so as to deliver anything from zero up to 6,000,000 gallons per 24 hours. The writer is of the opinion that a great many synchronous motor applications may be found where similar adaptations of the mechanically driven apparatus to the requirements of synchronous drive may be accomplished.

As an indication of what may be looked for in this line, there has been developed an air compressor which, operating at constant rotative speed of the shaft, varies its output by air valves operated by a mechanism similar to that of a corliss engine. The corliss gear varies the cut-off on the intake, and thereby limits the work done per stroke, while the compressor may be relieved entirely of load at starting by blocking the valves open.

Another method of accomplishing the same result has been suggested by Mr. I. Lundgaard, Junior member of the American Society of Mechanical Engineers, who recommends the adaptation of constant speed motor drive to variable output for air and ammonia compressors by means of an adjustable clearance space to be secured through the use of small cylinders with stop pistons, or through a series of chambers communicating with or cut off from the clearance space by separate valves. The combination of such an arrangement with a by-pass valve obviates the necessity for variable speed and high starting torque, and through such arrangement the range of industrial application of synchronous motors is very widely extended.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

THEORY OF THE NON-ELASTIC AND ELASTIC CATENARY AS APPLIED TO TRANSMISSION LINES

C. A. PIERCE, F. J. ADAMS AND G. I. GILCHREST

Though many engineers have written articles on the subject of tensions and sags in suspended wires, few have given any attention to the theory of the subject, being satisfied to refer to some text-book, or other guide, for authority. When the novice turns to these references, he usually finds them insufficient for the understanding of the articles in which the references occur and he is forced to spend more or less time in recreating the articles. It would seem then that there is need for an article dealing with the theory of the catenary as applied to transmission lines. Furthermore, there seems to be need for more experimental data to test the accuracy of the equations with the actual measured values on real spans. It is believed that these data can be obtained in the laboratory on short spans with small wires better than would be possible out of doors on long spans with larger wires, because of the readiness with which various conditions can be controlled in the laboratory.

This article deals with the theory of the catenary as applied to transmission lines, and experimental data are compared with the values derived by use of the theoretical equations.

THEORETICAL

When a perfectly flexible elastic string hangs between two horizontal supports and is acted on by gravitation only, it takes the form of a curve which has been called the elastic catenary. The equation for this curve is deduced as follows:

Referring to Fig. 1, let the length of the arc of the elastic catenary, P_2OP_1, be measured from 0, the lowest point of the

arc. Consider an element, dl, of the arc between two points, P and P'. The element dl is under tension and consequently is stretched. If the unstretched length of dl is $d\sigma$, then by Hooke's law,

$$dl = d\sigma\,(1 + \lambda\,T),$$

where λ is the elastic constant of the string and T is the tension which stretches length $d\sigma$ into length dl. If the weight of unit length of the unstretched string is W, then the weight of dl, which is equal to weight of $d\sigma$, is equal to $W\,d\sigma$. Substituting the value of $d\sigma$ as given in the formula above, the weight of element dl is equal to $W\,dl \div (1 + \lambda\,T)$.

The vertical component, V, of the tension at P differs from that at P' by the weight of the element dl, hence

$$dV = W\,\frac{dl}{1 + \lambda\,T}$$

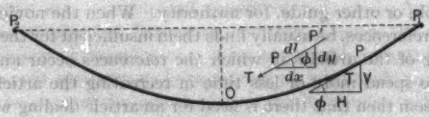


FIG. 1

But $V = H \tan\phi$, where H is the horizontal component of the tension at P and ϕ is the angle between the tension at P and the horizontal component H. Hence,

$$d\,(H \tan\phi) = W\,\frac{dl}{1 + \lambda\,T}$$

or, since H is constant along the arc,

$$d\,(\tan\phi) = \frac{W}{H}\,\frac{dl}{1 + \lambda\,T}$$

Letting $W \div H = 1 \div K$ and $\lambda\,H = N$, where K and N are constants, and substituting $T = H \sec\phi$,

$$\begin{aligned} dl &= K\,(1 + N \sec\phi)\,d\,(\tan\phi) \\ &= K\,(1 + N \sec\phi)\,\sec^2\phi\,d\phi \\ &= K \sec^2\phi\,d\phi + K\,N \sec^3\phi\,d\phi \qquad (1) \end{aligned}$$

Now,

$$\int \sec^2\phi \, d\phi = \tan\phi$$

and

$$\int \sec^3\phi \, d\phi = 1/2 \, (\sec\phi \tan\phi + gd^{-1}\phi)$$

To prove the latter equation, which is not one of the simpler integrals, one can differentiate the answer.

$$\begin{aligned} d\,[1/2\,(\sec\phi \tan\phi + gd^{-1}\phi)] \\ &= 1/2\,[\tan^2\phi \sec\phi \, d\phi + \sec^3\phi \, d\phi + \sec\phi \, d\phi] \\ &= 1/2\,[\sec^3\phi + \sec\phi\,(\tan^2\phi + 1)]\, d\phi \\ &= \sec^3\phi \, d\phi \end{aligned}$$

Hence, integrating (1)

$$l = K \tan\phi + \frac{K\,N}{2}\,(\sec\phi \tan\phi + gd^{-1}\phi) \tag{2}$$

This equation for the length, l, of an arc of the catenary is known as the intrinsic equation of the curve because it gives the length of the arc in terms of the angle of bending, ϕ, of the arc, and constants. This equation can be changed into equations based upon the rectangular co-ordinate system. To do this let the direction $P_2\,P_1$, Fig. 1, determine the direction of the X-axis and the vertical to $P_2\,P_1$ determine the direction of the Y-axis, the position of the origin of the co-ordinates being as yet unknown. As seen in Fig. 1, $dy = dl \sin\phi$. But, as proved above, $dl = K\,(\sec^2\phi + N \sec^3\phi)\,d\phi$. Hence,

$$\begin{aligned} dy &= K \sin\phi\,(\sec^2\phi + N \sec^3\phi)\, d\phi \\ &= K\,(\sec\phi \tan\phi + N \sec^2\phi \tan\phi)\, d\phi \end{aligned}$$

and

$$y = K\,(\sec\phi + N/2 \tan^2\phi) \tag{3}$$

Also, as seen in Fig. 1, $dx = dl \cos\phi$. Hence,

$$\begin{aligned} dx &= K \cos\phi\,(\sec^2\phi + N \sec^3\phi)\, d\phi \\ &= K\,(\sec\phi + N \sec^2\phi)\, d\phi \end{aligned}$$

and,

$$x = K\,(gd^{-1}\phi + N \tan\phi) \tag{4}$$

The constants of integration for the two equations of y and x are zero if the origin of co-ordinates is chosen properly. If the Y-axis is taken so that it passes through 0, the center of the

arc of the catenary, then equation (4) is satisfied. And if the origin of co-ordinates is taken a distance K below the point 0, then equation (3) is satisfied.

It is desirable to eliminate the angle ϕ from equations (3) and (4), but this cannot be done at all easily so the equations are left in the form given above.

Collecting formulas for the elastic catenary:

$$l = K\,[\tan\phi + N/2\,(\sec\phi\tan\phi + gd^{-1}\,\phi)] \tag{5}$$

$$y = K\,(\sec\phi + N/2\tan^2\phi) \tag{6}$$

$$x = K\,(gd^{-1}\,\phi + N\tan\phi) \tag{7}$$

$$T = H\sec\phi = K\,W\sec\phi \tag{8}$$

$$H = T \div \sec\phi \tag{9}$$

$$V = T\sin\phi \tag{10}$$

$$K = \text{the } y\text{-intercept of catenary} \tag{11}$$

Using subscripts, as l_1, etc., to refer to the value of l at one of the supports, etc.

$$L_1 = 2\,l_1 = 2\,K\,[\tan\phi_1 + N/2\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)] \tag{12}$$

$$y_1 = K\,(\sec\phi_1 + N/2\tan^2\phi_1) \tag{13}$$

$$X_1 = 2\,x_1 = 2\,K\,(gd^{-1}\,\phi_1 + N\tan\phi_1) \tag{14}$$

$$T_1 = K\,W\sec\phi_1 \tag{15}$$

$$H = \text{Const.} = T_1 \div \sec\phi_1 \tag{16}$$

$$V_1 = T_1\sin\phi_1 \tag{17}$$

$$S_1 = y_1 - K = K\,(\sec\phi_1 - 1 + N/2\tan^2\phi_1) \tag{18}$$

where L_1 is the length of arc between supports, *i.e.*, the length of the stretched string, y_1 is the Y-coordinate of a support, X_1 is the length of span, T_1 is the tension tangential to the string at either support, S_1 is the sag at the center of the span and is equal to the vertical distance from 0 to the line between the supports, etc.

The equations for length of arc, span, tension, sag, etc., are in terms of K, N, and functions of ϕ_1. As these equations are difficult to use, it is customary to assume for a first approximation that N is equal to zero, *i.e.*, that the string does not stretch appreciable under tension. Making this approximation, the equations of the simple catenary are deduced. They are:

$$L_1 = 2\,K \tan \phi_1 \tag{19}$$

$$y_1 = K \sec \phi_1 \tag{20}$$

$$X_1 = 2\,K\, gd^{-1}\, \phi_1 \tag{21}$$

$$T_1 = K\, W \sec \phi_1 \tag{22}$$

$$H = T_1 \div \sec \phi_1 \tag{23}$$

$$V_1 = T_1 \sin \phi_1 \tag{24}$$

$$S_1 = K\,(\sec \phi_1 - 1) \tag{25}$$

While the equations of the simple catenary can be changed into many different forms, the ones above are the simplest in form and show that the various quantities of interest to engineers in designing the mechanical characteristics of transmission lines are functions of K and ϕ_1, the tension including another factor, W, the weight of the unstretched conductor per unit length.

Unfortunately, the factor K is difficult to deal with directly. It can be eliminated in two ways; the most obvious way is to take ratios of the quantities, such as $L_1 \div X_1$, $X_1 \div T_1$, etc. The important equations below are obtained in this manner. These equations may be appropriately called *the characteristic ratios of the simple catenary.**

The characteristic ratios of the simple catenary are:

$$\frac{L_1}{X_1} = \frac{\tan \phi_1}{gd^{-1}\, \phi_1} \tag{26}$$

$$\frac{X_1}{T_1} = \frac{2\, gd^{-1}\, \phi_1}{\sec \phi_1} \times \frac{1}{W} \tag{27}$$

$$\frac{S_1}{X_1} = \frac{\sec \phi_1 - 1}{2\, gd^{-1}\, \phi_1} \tag{28}$$

$$\frac{S_1}{T_1} = \frac{\sec \phi_1 - 1}{\sec \phi_1} \times \frac{1}{W} \tag{29}$$

$$\frac{S_1}{L_1} = \frac{\sec \phi_1 - 1}{2 \tan \phi_1} \tag{30}$$

$$\frac{L_1}{T_1} = \frac{2 \tan \phi_1}{\sec \phi_1} \times \frac{1}{W} \tag{31}$$

*The equations are given for one point, the support, on the catenary, because the quantities in these equations are of especial interest to engineers. The general characteristic ratios of the simple catenary are derived from the equations of l, y, x, T, etc., above.

Table I gives the numerical values of these ratios for various values of the angle ϕ_1. From these values, curves can be plotted from which the values of the ratios for any angle less than 60 deg. can be interpolated. For accurate work the curves must be plotted to a reasonable scale. However, the values in

TABLE I

THEORETICAL CHARACTERISTIC RATIOS

(Based on W, weight per unit length, equal to unity.)

Angle ϕ_1	$\frac{L_1}{X_1}$	$\frac{X_1}{T_1}$	$\frac{S_1}{X_1}$	$\frac{S_1}{T_1}$	$\frac{S_1}{L_1}$	$\frac{L_1}{T_1}$
0						
1	1.00005	0.0349	0.00436	0.000152	0.00436	0.0349
2	1.00020	0.0698	0.00873	0.000609	0.00873	0.0698
3	1.00046	0.1046	0.01309	0.001370	0.01309	0.1047
4	1.00081	0.1394	0.01747	0.002436	0.01746	0.1395
5	1.00127	0.1741	0.02186	0.003805	0.02183	0.1743
6	1.00184	0.2087	0.02626	0.005478	0.02620	0.2091
7	1.00250	0.2431	0.03066	0.007454	0.03058	0.2437
8	1.00327	0.2774	0.03508	0.009732	0.03496	0.2783
9	1.00415	0.3116	0.03951	0.01231	0.03935	0.3129
10	1.00514	0.3455	0.04397	0.01519	0.04374	0.3473
12	1.00744	0.413	0.0529	0.02185	0.0525	0.416
14	1.01084	0.479	0.0620	0.02970	0.0614	0.484
15	1.01173	0.512	0.0666	0.03407	0.0658	0.518
16	1.01340	0.544	0.0712	0.03874	0.0703	0.551
18	1.01710	0.608	0.0805	0.04894	0.0792	0.618
20	1.02130	0.670	0.0900	0.0603	0.0882	0.684
25	1.03423	0.817	0.1146	0.0937	0.1108	0.845
30	1.0510	0.951	0.1408	0.1340	0.1340	1.000
35	1.0726	1.070	0.1691	0.1808	0.1576	1.147
40	1.0999	1.169	0.2001	0.2339	0.1820	1.285
45	1.1346	1.246	0.2350	0.2929	0.2071	1.414
50	1.1792	1.299	0.2749	0.3571	0.2331	1.532
55	1.2373	1.324	0.3220	0.4264	0.2603	1.638
60	1.3152	1.317	0.3796	0.5000	0.2887	1.732

Table I are computed for values of the angle, ϕ_1, sufficiently close together so that values may be interpolated from the table directly for all ordinary work without resorting to curves. The constant, W, is assumed to be unity in Table I. The values of the ratios for any weight per unit length of conductor is obtained by simple multiplication, using the reciprocal of W as

indicated in equations (**26**) to (**31**) inclusive. Any problem in connection with the simple catenary, in which any two of the quantities occurring in the characteristic ratios are given, can be solved by means of Table I. Thus, if length of conductor and span are given, the tension, sag, etc., can be obtained immediately from the table.

The other method of eliminating K from equations (**19**) to (**25**) inclusive is not quite so obvious as the first method. Since some of the equations below are of interest in their general form, *i.e.*, when they are not referred to the point of suspension, K will be eliminated from equations (**5**), (**6**), (**7**), etc. Letting N equal zero in equations (**6**) and (**7**),

$$y = K \sec \phi$$
$$x = K\, gd^{-1}\, \phi$$

Combining and remembering that $dy \div dx = \tan \phi$

$$y = K \sec gd \frac{x}{K} = K \cosh \frac{x}{K} \tag{32}$$

$$\frac{dy}{dx} = \sinh \frac{x}{K} = \tan \phi \tag{33}$$

$$\phi = \tan^{-1} \sinh \frac{x}{K} \tag{34}$$

From (**5**), letting N equal zero and substituting (**34**),

$$l = K \tan \phi = K \sinh \frac{x}{K} \tag{35}$$

$$L_1 = 2\, l_1 = 2\, K \sinh \frac{x_1}{K} = 2\, K \sinh \frac{X_1}{2\, K} \tag{36}$$

From (**8**) and (**6**), letting N equal zero and combining,

$$T = K\, W \sec \phi$$
$$y = K \sec \phi$$
$$T = W\, y \tag{37}$$

Substituting (**32**) in (**37**),

$$T = W\, K \cosh \frac{x}{K}$$

$$T_1 = W\, K \cosh \frac{x_1}{K} = W\, K \cosh \frac{X_1}{2\, K} \tag{38}$$

Combining (**36**) and (**38**),

$$\frac{L_1}{T_1} = \frac{2}{W} \tanh \frac{x_1}{K}$$

$$K = \frac{x_1}{\tanh^{-1} \dfrac{W L_1}{2 T_1}} = \frac{X_1}{2 \tanh^{-1} \dfrac{W L_1}{2 T_1}}$$

Substituting this value of K in (**38**), letting $L_1 \div 2 T_1 = Q_1$,

$$T_1 = \frac{W X_1}{2 \tanh^{-1} \dfrac{W L_1}{2 T_1}} \cosh \tanh^{-1} \frac{W L_1}{2 T_1}$$

$$= \frac{W X_1}{2 \tanh^{-1} W Q_1} \times \frac{1}{\sqrt{1 - W^2 Q_1^2}} \tag{39}$$

The proof of the reduction formula for $\cosh \tanh^{-1} x$ is in every way analogous to the proof of the reduction formula for $\cos \tan^{-1} x$.

By proofs similar to the one leading to (**39**)

$$L_1 = \frac{X_1}{\tanh^{-1} W Q_1} \times \frac{W Q_1}{\sqrt{1 - W^2 Q_1^2}} \tag{40}$$

$$S_1 = \frac{X_1}{2 \tanh^{-1} W Q_1} \left(\frac{1}{1 - W^2 Q_1^2} - 1 \right) \tag{41}$$

These last three equations give T_1, L_1, and S_1 in terms of span, X_1, weight per unit length unstretched conductor, W, and a ratio, Q_1, which is of course merely a number. Inspection of equations (**26**) to (**31**) will show that T_1, L_1 and S_1 are dependent on W only as a multiplying factor or not at all, hence in equations (**39**), (**40**) and (**41**), W can be placed equal to unity. Also X_1 can be placed equal to unity, and equations (**39**), (**40**) and (**41**) will be reduced to equations for unit span and unit weight of conductor per unit length. Since X_1 and W are only multiplying values, the tension, length of arc and sag for any values of X_1 and W are found from the values for unit span etc., by direct proportion as indicated in equations (**25**) to (**31**) and (**39**) to (**41**).

The equations (**39**) to (**41**) may be used to compute values of T_1, L_1 and S_1 with which the characteristic ratios of a simple catenary may be computed. Also, curves can be plotted between T_1, L_1 and S_1 as has already been done in an excellent article by

Mr. Thomas. Mr. Thomas did not mention in his article the method by which he obtained his values, but the equations (**39**) to (**41**) can be used for this purpose. Given suitable tables of the hyperbolic functions, these equations are simple to use, because of the presence of the same functions in all of the equations.

Example. To find the tension at point of suspension and the sag if a conductor 1001.27 ft., (305.19 m.), long is hung between two horizontal supports 1000 ft., (304.80 m.), apart, $W = 1$ lb., (0.4536 kg.). From the data given, $L_1 \div X_1 = 1.00127$. From Table I this is seen to give an angle at the supports equal to 5 deg. Hence, as read from the table, $X_1 \div T_1 = 0.1741$ or $T_1 = 5744$ lb., (2605.4 kg.). Also, from the table, $S_1 \div X_1 = 0.02186$, or $S_1 = 21.86$ ft., (6.66 m.). These results can be checked by means of equations (**39**) to (**41**). From the values just determined, the ratio $Q_1 = L_1 \div 2\,T_1 = 0.08716$. Substituting in equation (**39**), $T_1 = 5744$ lb., (2605.4 kg.). Substituting in equation (**41**), $S_1 = 21.86$ ft., (6.66 m.), and substituting in equation (**40**), $L_1 = 1001.29$ ft., (305.19 m.). This checks the problem and also the formulas.

The above check was made using six-place logarithm tables and the Smithsonian tables of hyperbolic functions. The check is seen to be very good. When computing the values in Table I, it was found that the Smithsonian tables did not give the values of the anti-gudermanian to sufficient decimal places to allow one to determine the ratio $L_1 \div X_1 = \tan \phi_1 \div gd^{-1}\,\phi_1$ accurately for small values of ϕ_1. It will be noticed, by reference to the table, that this ratio does not differ from unity by as much as 0.1 per cent until ϕ_1 becomes as great as five degrees. Furthermore, both $\tan \phi_1$ and $gd^{-1}\,\phi_1$ are nearly equal for small values of ϕ_1. Hence, in order to calculate this ratio accurately, it was found necessary to calculate the values of $gd^{-1}\,\phi_1$ by the equation,

$$gd^{-1}\phi_1 = \log_e \tan\,(\pi/4 + \phi_1/2)$$

The characteristic ratios of the simple catenary, the example above, and equations (**39**) to (**41**) are all based on the assumption that the conductor does not stretch, *i.e.*, that the elastic constant, $\lambda = N \div H$, is equal to zero. If this assumption is not made, then one must use equations (**12**) to (**18**) inclusive in connection with a problem, or else make corrections in the simple formulae based on $\lambda = 0$. The constant K can be eliminated from equations (**12**) to (**18**) by taking ratios as has already been done for the equations for the simple catenary. If this is done, the six

characteristic ratios for an elastic catenary are obtained. Using bracketed quantities when they are based on the assumption of an elastic constant different from zero, the characteristic ratios follow:

$$\left[\frac{L_1}{X_1}\right] = \frac{\tan\phi_1 + N/2\,(\sec\phi_1 \tan\phi_1 + gd^{-1}\,\phi_1)}{gd^{-1}\,\phi_1 + N\tan\phi_1} \tag{42}$$

$$\left[\frac{X_1}{T_1}\right] = \frac{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1}{\sec\phi_1} \times \frac{1}{W} \tag{43}$$

$$\left[\frac{S_1}{X_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1} \tag{44}$$

$$\left[\frac{S_1}{T_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{\sec\phi_1} \times \frac{1}{W} \tag{45}$$

$$\left[\frac{S_1}{L_1}\right] = \frac{\sec\phi_1 - 1 + N/2\tan^2\phi_1}{2\tan\phi_1 + N\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)} \tag{46}$$

$$\left[\frac{L_1}{T_1}\right] = \frac{2\tan\phi_1 + N\,(\sec\phi_1\tan\phi_1 + gd^{-1}\,\phi_1)}{\sec\phi_1} \times \frac{1}{W} \tag{47}$$

Letting $N = O$, these equations reduce to equations (**26**) to (**31**) inclusive, the six characteristic ratios for the simple catenary.

It is, in general, impossible to use the characteristic ratios for the elastic catenary. Inspection of equations (**43**), (**45**) and (**47**) will show, however, that these three equations can be expressed in terms of the ratios of the simple catenary. Consider equation (**43**),

$$\left[\frac{X_1}{T_1}\right] = \frac{2\,gd^{-1}\,\phi_1 + 2\,N\tan\phi_1}{\sec\phi_1} \times \frac{1}{W}$$

$$= \frac{2\,gd^{-1}\,\phi_1}{\sec\phi_1} \times \frac{1}{W} + N\,\frac{2\tan\phi_1}{\sec\phi_1} \times \frac{1}{W}$$

$$= \frac{X_1}{T_1} + N\,\frac{L_1}{T_1} \tag{48}$$

$$= \frac{X_1}{T_1} + \frac{L_1}{T_1}\,\lambda\,T_1\cos\phi_1 \text{ (approx.)}$$

$$= \frac{X_1}{T_1} + \lambda\,L_1\cos\phi_1 \text{ (approx.)} \tag{49}$$

From formulas (**45**) and (**47**),

$$\left[\frac{S_1}{T_1}\right] = \frac{S_1}{T_1} + \frac{\lambda}{4} L_1 \sin \phi_1 \text{ (approx.)} \tag{50}$$

$$\left[\frac{L_1}{T_1}\right] = \frac{L_1}{T_1} + \frac{\lambda}{W} T_1 \sin \phi_1 + \frac{\lambda}{2} X_1 \cos \phi_1 \text{ (approx.)} \tag{51}$$

These formulas show that the characteristic ratios for the elastic catenary can be expressed in terms of the corresponding ratios for the simple catenary together with a correction factor. Inspection will show that any correction factor is but a small fraction of the whole expression, hence the approximation is close. A problem will illustrate this point.

Let $X_1 = 1000$, $W = 1$, $\lambda = 2.41 \times 10^{-7}$, to determine the tension, sag and length of conductor when the wire is strung between horizontal supports so that $\phi_1 = 5$ deg. From Table I,

$$\frac{L_1}{X_1} = 1.00127, \text{ hence } L_1 = 1001.3$$

$$\frac{X_1}{T_1} = 0.1741, \quad \text{“} \quad T_1 = 5744$$

$$\frac{S_1}{X_1} = 0.02186, \quad \text{“} \quad S_1 = 21.86$$

Using formulas (**49**), (**50**) and (**51**),

$$\left[\frac{X_1}{T_1}\right] = 0.1743, \text{ hence } [T_1] = 5737$$

$$\left[\frac{S_1}{T_1}\right] = 0.003810, \quad \text{“} \quad [S_1] = 21.86$$

$$\left[\frac{L_1}{T_1}\right] = 0.1745 \quad \text{“} \quad [L_1] = 1001$$

This problem shows that if a conductor is suspended between horizontal supports 1000 units apart so that the angle ϕ_1 is equal to five degrees, the sag and tension will be essentially the same

whether one assumes the elastic constant equal to zero or equal to its true value. Inspection of equations (**48**) to (**51**) will show that this conclusion is approximately true for all sags, tensions, spans, etc.

It is to be noticed that equations (**48**), (**50**) and (**51**) are sufficient to determine the remaining three characteristic ratios of the elastic catenary.

The problem of finding how the sag and tension, etc., vary with temperature change is simple if the elastic constant is assumed equal to zero. The problem is solved at one temperature by means of Table I, using the values of L_1, W, etc., at this temperature. Then the new length and new weight per unit length are determined at the new temperature by means of the usual formulas,

$$L'_1 = L_1\left(\frac{1 + \alpha t'}{1 + \alpha t}\right)$$

$$W' = W\left(\frac{1 + \alpha t}{1 + \alpha t'}\right)$$

where L_1 and W refer to temperature t, L'_1 and W' refer to temperature t' and α is the temperature coefficient of expansion. These new values of length and weight are substituted in the characteristic ratios for the simple catenary and the problem solved by use of Table I, assuming the span, X_1, to remain unchanged.

In all of the problems and equations above, W stands for the weight of unstretched conductor per unit length. This value includes not only the weight of the material of the conductor but also the weight of ice that may surround the conductor. If wind pressure is assumed to blow the conductor out of the vertical plane so that it still hangs in the form of a catenary curve then W will include the factor of wind pressure, the resultant weight per unit length of unstretched conductor being the vector sum of the weight of conductor, weight of ice and equivalent weight of wind pressure. It is evident that the first two factors add arithmetically and act downward in the direction of the force of gravity while the equivalent weight of wind pressure will in general be at right angles to the plane of the conductor when it hangs in its normal position, the resultant weight, W, acting in the plane in which the conductor actually hangs.

The problem of finding the change in sag, tension, etc., due to a change in W is difficult to treat accurately. The authors know of no better procedures than the approximate ones suggested by several writers, including Mr. H. W. Buck and Mr. P. H. Thomas; references to these articles are given below. This general problem could be solved immediately by use of the characteristic ratios of an elastic catenary, equations (**42**) to (**47**) inclusive, if it were not that these equations are too complex to use.

Experimental

In order to check the theoretical equations derived above with experimental data, an experimental span was erected in the laboratory. A large I-beam which ran the length of the laboratory, about 200 ft. (61.0 m.), was used as a support for the wire span. The length of the actual span was 190.70 ft. (58.12 m.). No. 4 A.w.g. hard drawn copper wire was chosen for the first tests, which are the only tests included in this article. In order to straighten the wire it was stretched to about its elastic limit and then allowed to hang several days before the measurements were begun. Each end of the wire was caught in a clamp which was free to turn in a vertical plane determined by the wire. At one end of the span, the clamp was supported by means of a system of links in such manner that the horizontal tension could be computed directly from the readings of a small platform balance. The vertical tension was taken as the weight of half of the wire included between the clamps. The sags at different points in the span were measured by a rod from stations which had been leveled by means of a surveyor's level. The sags were measured at nine equidistant stations between the points of suspension. These stations were numbered 1 to 9 consecutively, making station 5 come at the center of the span. The points of suspension were at stations 0 and 10. A gallery in the laboratory furnished the support for the stations and the wire hung down in front of this gallery. This arrangement allowed the sag measurements to be made with a much shorter rod than would have been necessary if the sags had been measured directly from the line of the suspensions. The rod with which the sags were measured ran through a guide which was set up vertically at each station, and contact with the wire was judged by means of an electrical contact arrangement. With this device no difficulty was experienced in measuring sags to about 0.02 inch (0.051 cm.), though the small vibrations of the wire caused by machinery in

the laboratory made some measurements vary by as much as 0.06 inch (0.152 cm.).

All weights were obtained on the same platform balance so that the calibration of the balance was unnecessary. It was assumed that the balance, a new one, would give a straight line for the calibration curve. All lengths were referred to either a B. & S. steel tape or to a Starrett steel tape. These tapes were accepted as accurate.

TABLE II.

CHARACTERISTIC RATIOS

Comparison of Experiment and Theory

Run		$\frac{L_1}{X_1}$	$\frac{X_1}{T_1}$	$\frac{S_1}{X_1} \times 10^{-3}$	$\frac{S_1}{T_1} \times 10^{-3}$	$\frac{S_1}{L_1} \times 10^{-3}$	$\frac{L_1}{T_1}$	
No. 1	A	1.022	5.48	9.12	5.01	8.93	5.61	Exp.
"	B	1.022	5.42	9.21	5.01	9.01	5.54	theory
"	C	1.022	5.39	9.12	4.91	8.92	5.49	"
"	D	1.023	5.48	9.35	5.16	9.14	5.62	"
No. 2	A	1.011	3.95	6.32	2.49	6.25	3.99	Exp.
"	B	1.011	3.91	6.38	2.49	6.31	3.95	theory
"	C	1.011	3.88	6.32	2.45	6.25	3.92	"
"	D	1.011	3.95	6.45	2.55	6.38	3.99	"
No. 3	A	1.005	2.72	4.26	1.161	4.24	2.73	Exp.
"	B	1.005	2.69	4.31	1.161	4.29	2.70	theory
"	C	1.005	2.66	4.26	1.138	4.24	2.68	"
"	D	1.005	2.72	4.36	1.189	4.34	2.74	"
No. 4	A	1.002	1.609	2.45	0.395	2.45	1.612	Exp.
"	B	1.002	1.574	2.49	0.395	2.49	1.576	theory
"	C	1.002	1.551	2.45	0.384	2.45	1.553	"
"	D	1.002	1.611	2.55	0.412	2.55	1.612	"
No. 5	A	1.003	0.845	1.32	0.112	1.32	0.845	Exp.
"	B	1.005	0.840	1.32	0.112	1.32	0.840	theory
"	C	1.005	0.838	1.32	0.112	1.32	0.839	"
"	D	1.005	0.844	1.33	0.113	1.33	0.845	"

Each run in the tests consisted in drawing the wire up to some desired sag. Then balance readings were taken to determine the horizontal tension, and sags were measured from the leveled stations. From the former measurements the tension at the suspension could be immediately computed, using the half weight of the wire in the span as the vertical tension. The weight of the wire in the span was determined by weighing and measuring the total wire used, and at each run the wire that extended be-

yond the clamps was deducted. The angle, ϕ_1, between the tension in the wire and the horizontal could be determined from the balance readings and weight of wire. From the sag measurements the actual sags below the horizontal line through the points of suspension could be computed.

Using the measured values of ϕ_1, X_1, L_1, T_1 and S_1, the characteristic ratios for the span could be computed directly. These values are shown in Table II, lines A. Using the measured values of ϕ_1, the theoretical values of the characteristic ratios for a simple catenary are shown in lines D. Using the measured

TABLE III

SAGS (unit = ft.)

Comparison of Experiment and Theory

Stations

Run		0 and 10	1 and 9	2 and 8	3 and 7	4 and 6	5	
No. 1	A	0	6.31	11.18	14.63	16.72	17.38	Exp.
"	B	0	6.29	11.16	14.62	16.69	17.38	theory
"	C	0	6.45	11.43	14.97	17.00	17.79	"
No. 2	A	0	4.37	7.73	10.14	11.59	12.05	Exp.
"	B	0	4.35	7.73	10.13	11.57	12.05	theory
"	C	0	4.44	7.86	10.34	11.81	12.30	"
No. 3	A	0	2.95	5.23	6.85	7.82	8.13	Exp.
"	B	0	2.92	5.21	6.33	7.81	8.13	theory
"	C	0	3.00	5.33	6.99	7.99	8.32	"
No. 4	A	0	1.72	3.02	3.95	4.51	4.68	Exp.
"	B	0	1.69	3.00	3.93	4.50	4.68	theory
"	C	0	1.75	3.11	4.08	4.67	4.86	"
No. 5	A	0	0.91	1.61	2.11	2.42	2.52	Exp.
"	B	0	0.91	1.61	2.12	2.42	2.52	theory
"	C	0	0.92	1.63	2.13	2.44	2.54	"

values of S_1 and T_1, the angle ϕ_1 can be interpolated from Table I and the remaining theoretical characteristic ratios for the simple catenary can also be interpolated from Table I. These results are shown in lines B, Table II. The lines C give theoretical values based on the measured values of S_1 and X_1.

Table III, lines A, shows the measured sags at the various stations. Since the sags at stations 0 and 10, 1 and 9, 2 and 8, etc., should correspond respectively, the averages of these values are shown in the table. The theoretical sags of a simple catenary which would pass through the points of suspension and the point

of maximum sag as determined experimentally are given in lines *B*, Table III. The theoretical sags of a simple catenary making an angle, ϕ_1, at the suspension, equal to the experimental angle, are given in lines *C*, Table III.

The data could have been worked up in various ways and various comparisons made, but the tables shown above give as comprehensive an idea of the results as is possible in the space used.

Conclusion

Inspection of Table II will show that the check between experiment and theory, which is based on the characteristic ratios of the simple catenary, is very good, if the number of variable quantities is considered. Inspection of Table III will show that the theoretical sag is greater then the actual measured sag. The wire hung approximately in the form of a simple catenary, however, as is shown in the same table. In run 4, Table III, the wire seems to have departed from the catenary form at stations 1 and 9, also at 2 and 8. This seeming departure from the form of the simple catenary was due to the clamp at one end of the span becoming wedged against a bolt head as the sag was diminished. The effect is noticeable in run 3. Before making run 5, the trouble was located and the wire again hangs in the form of a simple catenary as nearly as the measurements will show.

The authors are not prepared to explain why the measured sags were less than the sags computed from the measured angle ϕ_1. If the angle ϕ_1, as measured, was too large, this would mean that the measured horizontal tension or the measured vertical tension was not accurate, but careful check of the apparatus did not prove this assumption. It should be pointed out, furthermore, that no attempt was made to correct for temperature changes of the laboratory during the experiments. The changes were small. When tested at several different times, the temperature was found not to vary more than two deg. cent.

Further experiments with wires of different sizes are being carried on at the present time. Next winter, it is proposed to test the change of sag and tension with temperature change. The apparatus was not completed in time to take advantage of the cold weather during the past winter to obtain the lower temperatures.

The authors wish to add that the use of hyperbolic functions has become too general in engineering to need apology. The use

of the Gudermannian function and its inverse are not so general, but their value is evident. The significance of these functions is partially deducible from the equations, $gd\ x = \tan^{-1}(\sinh x)$, $gd^{-1}\ x = \sinh^{-1}(\tan x)$. For further information about hyperbolic functions and the Gudermannian, see references.

References

Hyperbolic Functions, Professor James McMahon.

Sag Calculations for Suspended Wires. Percy H. Thomas. TRANS. A. I. E. E., Vol. XXX, p. 2229, 1911.

The Use of Aluminum as an Electrical Conductor, H. W. Buck. *Trans. Int. Elect. Congress*, St. Louis, 1904, Vol. 2, p.313.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 25, 1913.

Copyright, 1913. By A. I. E. E.

ELECTRICAL REQUIREMENTS OF CERTAIN MACHINES IN THE RUBBER INDUSTRY

BY C. A. KELSEY

This paper is intended to outline briefly the power requirements of some of the principal machines which work up crude rubber and render it suitable for the manufacture of various articles.

The principal source of rubber is the wild trees of Brazil, although cultivated rubber in increasing quantities is now produced in East India, Ceylon, Malayan Peninsula and Southern Mexico. The former reaches the factory in the form of balls or biscuits about a foot in diameter. Cultivated rubber is universally washed and sheeted at the plantation and is shipped in the form of cakes of folded sheets.

Washing. After the biscuits have been cut into chunks and softened in a bath of warm water, they are fed into a cracker or rough washing mill. This mill consists of two or three rolls between which the rubber passes, is torn apart and rolled out into a rough sheet. Water flowing through the rubber in its passage through the rolls washes out part of the entrapped dirt.

These mills run at a constant speed of 20 to 25 rev. per min. The load is very irregular and depends upon the feeding of the mill. A three-roll washer with continuous feeding requires an average of 25 to 35 h.p., with power peaks of 100 h.p.

The rough sheet is then passed through a single set of rolls where it is further washed and rolled out into a sheet or "crepe."

These mills run at a constant speed of about 25 rev. per min. The load is fairly uniform as the rubber is already in the form of a rough sheet. The power required averages 20 to 25 h.p. and

occasionally runs up to 50 h.p. when the sheet is introduced between the rolls after being doubled.

After the crepe has been dried either in a drying room, where it is suspended from the ceiling, or placed in a vacuum drier, it is ready to be masticated and mixed with the suitable ingredients to form various compounds.

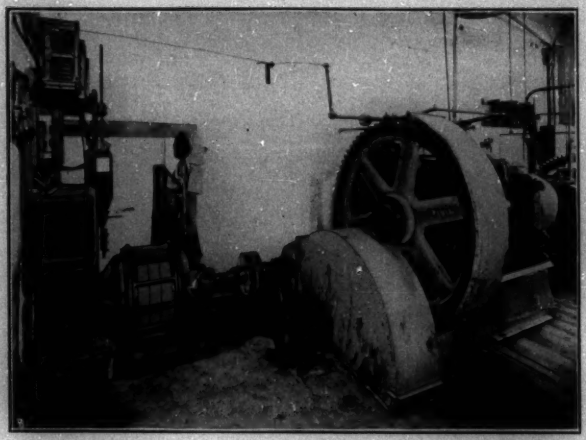
Masticating. The dried crepe must be worked or masticated into a homogeneous and plastic state before the ingredients are added. This is most economically done in a shorter mill than a mixing mill. The power required at the beginning of the process is greater than at the end and runs up to a high value as the rubber is cut free from the roll and doubled back in again. From tests on a 50-in. (1.27-m.) face mill the average power was 37 h.p. and the maximum 74 h.p., while a 60-in. (1.52-m.) face mill required an average power of 90 h.p. and a maximum of 140 h.p.

Mixing. Pure rubber is never used in the manufacture of rubber articles without first adding to it some other substance. Different materials are employed, depending upon the use and desired characteristics of the rubber product. Some materials increase the elasticity, some impart hardness and toughness and some act as mechanical fillers to cheapen the product without materially affecting the desired characteristics.

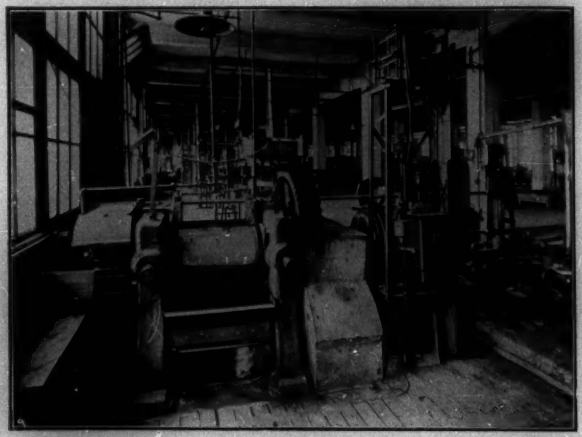
Where the rubber is masticated in the mixing mill, the predetermined weights of the various substances are added in a powdered or liquid state only after the masticated rubber has been thoroughly worked and warmed. As the ingredients impart different degrees of hardness and toughness to the final product so will the power to drive the mill vary.

The speed of the rolls ranges from 20 to 25 rev. per min. A 40-in. (1-m.) face mill requires about 20 h.p. average and 40 h.p. maximum on relatively soft compound and 25 h.p. average and 55 h.p. maximum on hard compound while a 60-in. (1.5-m.) face mill requires 55 h.p. average and 120 h.p. maximum on medium compound.

Refining. In some installations the compound after leaving the mixing mill is passed through machines that strain it and reduce it to a very thin sheet. The strainers are in principle like a meat grinder. A feed screw revolving inside a water-jacketed cylinder forces the compound through a fine mesh screen which is backed up by a perforated plate. This removes all solid foreign objects which ordinarily find their way into the



THREE ROLL WASHER [KELSEY]

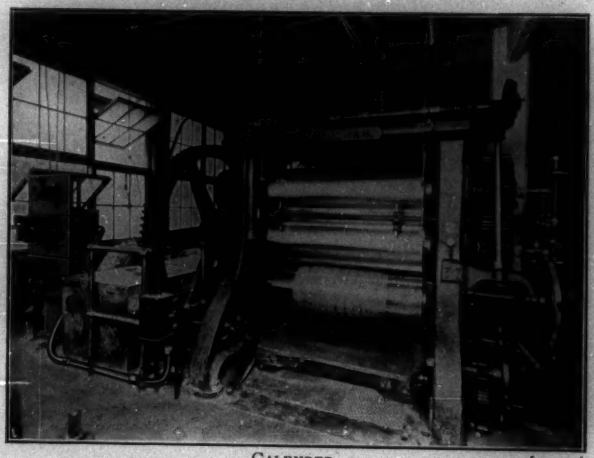


SHEETER [KELSEY]

MIXING MILL [KELSEY]

REFINING MILL [KELSEY]

WARMING MILL [KELSEY]



CALENDER [KELSEY]

material. The compound becomes heated more or less as it passes through the strainer and the final temperature must be kept below a given value. The heating varies with the compound and the initial temperature. An efficient means of maintaining maximum output is to vary the speed. This therefore requires an adjustable-speed motor. A two-to-one speed range is sufficient. The power required is 25 h.p. over the whole range. The harder compounds, requiring high torque are run at the slow speeds and the soft compounds requiring less torque are run at the high speeds.

After passing through the strainers the compound is passed through a refiner, which is a small mill whose rolls are held very close together. The compound is run through at a thickness of approximately three mils, being passed through several times and finally scraped off the roll as it comes through. It is then bundled up and is ready for the warming mill.

The mills are run at constant speed and uniform load. The power required does not exceed 25 h.p.

Warming. Although the compound is warmed in the mixing mills, it cannot always be used at once in the calenders, and, moreover, it is beneficial to the compound to let it season before calendering. Warming mills are therefore essential to warm the compound when it finally comes to the calenders. These mills are identical with the mixing rolls except that they are equipped with steam-heated rolls. The power required is slightly less than for the mixing rolls.

Tubing. When the article to be produced is tubular or ring-shaped the compound is forced through tubes. This machine is similar to a strainer excepting that instead of a screen and perforated plate the machine is fitted with a disk which delivers the compound in the form of a tube.

The speed and power requirements approximate those of a strainer.

Calendering. Practically all rubber compounds, with the exception of those run through tubes and for the manufacture of molded articles, are sheeted in a calender.

This machine has a series of rolls two or four in number arranged one over the other, between which the compound is passed to form a sheet. The surface of the rolls is finished smooth and the space between the rolls is adjustable to a very fine degree. The rolls are fitted with steam and water connection to heat or cool the compound as required.

The power required to drive a calender varies over a wide range depending on the character of the compound, thickness, width and speed. The speed is limited to that at which the compound can be run without blistering or the forming of a rough surface. When the calender is started up with cold rolls the permissible speed is higher than after the cooling rolls become heated. As these rolls become heated, it is necessary, in order to obtain the desired surface of the sheet, to reduce the speed. A fine speed graduation is therefore necessary to maintain a maximum output. The torque required depends upon the thickness and material and there are so many combinations possible together with the speed requirements that it is difficult to formulate any rule to determine the power. The motor must be large enough to meet the extreme conditions.

From a number of tests made it is found that an 18-in. (45.6-cm.) diameter, 40-in. (1-m.) face, three-roll calender running at a surface speed of 37 ft. (11.2 m.) per minute, requires an average of 20 h.p. A 24-in. (60-cm.) diameter, 48-in. (1.2-m.) face three-roll calender running at a surface speed of 35 ft. (10.6 m.) per minute requires an average of 35 h.p. and a 22-in. (55.8-cm.) diameter, 65-in. (1.64-m.) face, three-roll calender running at a surface speed of 36 feet. (10.9 m.) per minute requires an average of 45 h.p.

Some compounds that are run through the calender in successive layers which build up to ½ inch (1.27 cm.) or even ¾ in. (1.9 cm.) must be run at approximately 20 ft. (6 m.) per minute, while for "friction" work the speed of the driven roll may be 80 ft. (24.3 m.) per minute. The thick sheets will require slightly greater torque than the average thickness, while the torque for so-called "friction" work is considerably less.

The term frictioning is applied to that process performed by a calender in forcing a soft rubber compound into the meshes of cotton fabric. It is preliminary to the skimming or coating of the fabric. The rubber compound is very soft and plastic and is rubbed in by the action of the driven roll, which travels at a faster speed than the roll carrying the fabric.

As the compound and fabric are fed through in a continuous sheet the power required for a given material, thickness and width is quite uniform.

Motor Characteristics

In considering the power and speed requirements of the different machines, it is seen that the mills for working up the rubber

and mixing it to form the various compounds, call for extreme overloads but of short duration. By grouping these mills and driving by a single motor the load peaks can be reduced. Instead of the maximum values being 200 per cent of the average, it has been determined that this can be reduced to 150 per cent by driving with one motor a group of six mills used for masticating, mixing and warming.

Where individual drive is used, alternating-current polyphase squirrel cage motors are best suited to carry the high load peaks. By grouping the mills, a motor of a smaller capacity than the aggregate of the individual motors can be employed. Moreover, synchronous motors can then be installed and assist in correcting the power factor of the general power load. The mills are generally equipped with jaw clutches which can be open or closed while the shaft is running. The synchronous motor can thus be disconnected from the mills at starting. The selection of squirrel cage or wound rotor induction motor depends upon the local starting restrictions, as the squirrel cage motor will easily bring the shaft up to speed even with all mills connected.

Direct-current motors are sometimes used when this is the power available, but they are more expensive and not so well suited to the load conditions.

The calenders, as mentioned, require close speed control over a range of four to one. This can best be accomplished by a direct-current motor, which is the general practise. A number of schemes have been employed to accomplish this. Among them might be mentioned the multi-voltage and adjustable voltage methods.

The motor is excited at constant field strength and the armature supplied with a variable voltage. This variable voltage can be produced by a series of different voltage generators or by a rotary compensator or booster set.

A modification of the preceding is a three-wire, two-voltage source of armature supply combined with adjustable speed by field control. The first-mentioned methods produce a wide speed range but are expensive because of the number of machines required for each calender. The second method produces a less speed range but is less expensive, particularly where a large number of calenders are installed.

With the more recent general application of commutating poles to direct-current motors a greater speed range is permissible with constant armature voltage and varying field strengths.

This last-mentioned method results in the simplest equipment

as a whole. The motor must be larger but is therefore more substantial, while the control can be made extremely simple, or it can be made entirely automatic, thus calling for a minimum of attention and care from the operator.

The tubers also require a direct-current motor and the last-mentioned method of speed control is particularly adapted to these machines.

As the power to drive the mills is by far the greatest portion of the total power, alternating current will generally be selected. This therefore requires a motor-generator set or synchronous converter to deliver direct current to the calenders and tubers. These machines can be used to correct the power factor of the general power circuit.

Motor Control

As the motors to drive the mills are run at constant speed, starting devices only are required. A speed-controlling device must, however, be furnished with the motors driving the tubers and calenders. The former machines are simple in operation and a controller for hand operation which combines starting and speed adjustment is sufficient. The calenders, however, require closer attention and must be capable of starting and stopping by the simplest means on the part of the operator. This is best met by a control which enables the operator to bring the calender up to speed by moving the controller handle around to obtain the desired speed. Automatic acceleration should be provided to limit the current input while the controller handle is being moved around. It should then be possible to shut the calender down by pushing a button located on the calender. The speed of the calender should be retarded by dynamic braking of the motor. This is to provide a safety feature in respect to the operator in case his hand should be caught between the rolls. Also, it is desirable to stop quickly to save material otherwise wasted by the coasting of the motor. It should then be possible to bring the calender up to the same speed as before by pushing a button on the calender. Means should be provided for reversing the direction of rotation of the motor to assist in manipulating the calender and also in case anything should be caught between the rolls and it becomes necessary to back it out. The control should also include overload and low voltage release features and be immune from damage to itself or the motor in case the operator fails to close or open the proper switches.

DISCUSSION ON "THE BEHAVIOR OF SYNCHRONOUS MOTORS DURING STARTING" (NEWBURY), "COMMUTATING POLE SATURATION IN DIRECT-CURRENT MACHINES" (STOKES), "CONSTANT VOLTAGE TRANSMISSION" (DWIGHT) AND "THE INDUSTRIAL USE OF SYNCHRONOUS MOTORS BY CENTRAL STATIONS" (PARKER), COOPERSTOWN, NEW YORK, JUNE 25, 1913.

William J. Foster: The self-starting synchronous motor has one bad characteristic and that is the induced potential across the field terminals. It is something which exists in the nature of the apparatus. Of course, if we keep down the number of turns in the field winding, we always can help out in the matter of induced potential, but, as is stated by Mr. Newbury, it is not always convenient to do this. As a general rule, 125 volts has been regarded as standard, and we can design and wind the fields and insulate them so as to take care, ordinarily, of 125-volt windings, but when it comes to 250 volts it begins to be a serious matter. The insulation problem is serious. In such cases I have known of this scheme of short-circuiting the field to have been the practical solution of the problem, but in general, as pointed out by the author, the short-circuiting of the field detracts from the starting torque per input. That being the case, it is extremely desirable to excite at lower potential.

There is a particular use which can be made of the short-circuited field that I have known to have been resorted to in a number of cases of motors that have an increasing torque from rest to synchronous speed, and that is to short-circuit the field when about two-thirds speed has been attained. By doing that the torque can somewhat be increased at the higher speed, before you reach the point where excitation can be applied.

I think there are many places where synchronous motors are now installed and some difficulty, perhaps, is experienced in starting up at the pulling-in point, where by installing a resistance and short-circuiting the field much better results can be obtained.

August H. Kruesi: I want to suggest that the author give us the number of slots per pole, the radial depth of air gap and the number of bars in the short-circuiting winding for both machines so that we can tell to what extent the performance depends upon the particular design of the machine tested.

F. D. Newbury: The number of armature slots per pole is twelve, and the radial depth of air gap 3/16 in. (4.76 mm.) The number of damper bars per pole is seven and the damper winding is of the same type as shown in Fig. 1. The armature slot pitch is 0.88 in. (22.35 mm.) and the damper slot pitch is 1.15 in. (29.2 mm.)

H. M. Hobart: Mr. Stokes's paper draws attention to one of the greatest difficulties in connection with the design of machines with commutating poles. The commutating pole certainly

has been of very great service in improving the design of commutating machinery, but there are two sides to the matter and it has always seemed to me that it should not be used to any greater extent than is necessary for the accomplishment of the purpose for which it is put there. At its advent, designers used it to a very great extent and overdid the thing. The reasoning was that since with the commutating pole one could offset very large reactance voltages in the coil undergoing commutation, there was no need for any great subdivision of the commutator. It was considered that by having fewer segments and cheapening the construction of the commutator one could get as good results by neutralising the reactance voltage in the short-circuited coil by appropriately designed commutating poles, but it soon became apparent that there would be a tremendous magnetic leakage from these small commutating poles to the large main poles. Some designers appreciated that, but they were in a small minority. Most designers made the commutating poles the full length of the machine, but, as Mr. Stokes points out, there is 200 or 300 per cent magnetic leakage under these circumstances, unless you are quite careful in the design of the machine.

I considered right from the beginning, that the use of the commutating pole should be as follows: to design the machine as well as you could, quite aside from the commutating pole, and then put in enough commutating pole to neutralize the amount of reactance voltage, which you ordinarily have in the machine, or as much of it as is necessary to insure good commutation. My experience has been that it has usually worked out admirably to have the commutating pole extend only a very short distance in a direction parallel to the shaft. Make it as short as possible for the requirements. One should follow the procedure of first designing the machine as good as possible, without any reference to the intention which you have in reserve of adding the commutating pole.

Designers have been tempted to employ high reactance voltages. If, for example, a machine were planned with a reactance of 4 volts in the short-circuited coil, it might require that the commutating pole should extend the full width of the machine. If, however, a better design had been employed and the reactance voltage had been limited to 2 volts, then the machine could have been fitted with commutating poles of only half as great a length. This would have resulted in reducing the magnetic leakage and in less obstruction to the circulation of air amongst the poles.

Even at this late date, although the commutating pole has been used extensively for 10 years, there is still great need to emphasize this viewpoint. I am interested to see that the matter is being reduced to quantitative constants that will be of great aid, I have no doubt, to the designer.

F. D. Newbury: My own experience with direct-current design has been largely second-hand, and the experience I have

had has been in connection with alternating-current problems. It has always seemed to me that designers of direct-current machines have been more inclined to approach their problems through empirical methods than have designers of alternating-current machinery. Possibly this is due to their older experience, and the further distance they are away, in their methods, from the simple fundamentals. That at least has seemed to be the tendency.

It is the greater pleasure, therefore to note that in the present paper the author has got down to fundamentals, has made up his formulas from the results of careful experiment, and has approached the subject from the scientific and physical standpoint rather than from the empirical.

While the paper is primarily of interest to the designer, it is, I think, also of interest to the men using direct-current apparatus. There is a direct and particular relation between the commutating pole saturation and the ability of a given machine to withstand heavy overloads. It is, of course, on overloads that the saturation of the commutating pole becomes apparent and the non-compensated reactance volts cause dangerous sparking. All direct-current machines, even the compensated type, will flash on dead short circuit where the current will be anything from 15 to 20 times full load current. I have had many tests made, which have borne out the statement that most machines will flash very seriously with currents from five to ten times full load current. Those machines in which the commutating poles have been liberally proportioned, and more important still, as Mr. Hobart pointed out, machines in which the reactance volts have been made a minimum are the machines that will withstand the heaviest shocks and behave best on short circuits.

J. M. Hipple: In connection with Mr. Hobart's remarks, I call to mind a very extensive series of tests which showed clearly the advantage gained by the use of commutating poles. This test was made to determine if the commutating pole had any logical use in constant speed motor design. For some time its usefulness in adjustable speed motors had been conceded. A considerable number of representative motors of various makes were given endurance tests under these three conditions:

1. Full load and normal voltage.
2. Full load and 10 per cent below normal voltage.
3. Full load, normal voltage and 15 per cent increased speed by weakening the shunt field.

The motors tested were all of the non-commutating pole type and under condition (1) practically all gave good results, while under conditions (2) and (3) burning and blackening of the commutator developed in time. Similar tests on a series of commutating pole motors showed that under all three conditions, the commutator showed no signs of blackening or burning. Conditions (2) and (3) are not to be considered abnormal and must be provided for and the commutating pole when properly proportioned takes care of them perfectly.

H. M. Hobart: Commutating poles are used as an antidote for certain troubles, and if the antidote is used to too great an extent it may cause a condition which is worse than that which it was designed to cure. That is the point.

John M. Hipple: There are two ways of considering the commutating pole, one as an antidote for commutation troubles and another as a prime factor in design. In my opinion it has a proper and very important field as a prime factor in design, just as in the non-commutating pole motor the saturated pole tip is often used as a prime factor.

H. E. Stokes: In regard to Mr. Hobart's remarks on the short interpoles, it seems to be the general experience that it is well to make them shorter than the armature, say about 50 or 60 per cent of the length of the armature, and that has the effect of permitting the heat to get away from the armatures as Mr. Hobart pointed out. Something can be done to get away from the leakage question by making the interpole shorter, as regards the armature, and lengthening it up near the frame.

In regard to what Mr. Newbury had to say about machines flashing over, whether they are compensated or not, that is mostly due to the commutating pole flux lagging behind the reactance voltage, which causes a flash-over which can scarcely be taken care of by the commutator form.

F. D. Newbury: Mr. Dwight's paper presents very clearly the advantages of synchronous condensers in holding constant voltage at the end of a long transmission line. There is one application which I understand has already been made where such a use of synchronous condensers was a necessity—the combination of a long line at high voltage and at high frequency so that operation with a light load at the receiving end made it absolutely necessary to install such synchronous condensers in order to hold the voltage down to normal, due primarily, of course, to the small generating capacity in comparison with the length of the line. In that case synchronous condensers of half the capacity of the generators at the generating station were installed. That is a special application of the general plan advanced by Mr. Dwight, and I am quite sure merely points the way to a more general use of such synchronous condensers. As Mr. Dwight points out, the use of such a large additional generator capacity can only be justified in the case of long lines, where the cost of the line will be a more important item in the total cost than the cost of the main and substation machinery.

Mr. Dwight refers to railway work as possibly the single exception to the general use of 60 cycles. I would point out that it is becoming more and more frequent to use 60 cycles for railway work, employing 60-cycle synchronous converters. In the work of one of the larger manufacturing companies it has become very apparent that the use of synchronous converters, in the smaller sizes up to 1000 kw., has gradually shifted from 25 cycles to 60 cycles; whereas a few years ago the 500-kw., 25-cycle

machine for example was built in large numbers, at the present time the 60-cycle converter is the more usual machine, so that I think Mr. Dwight's single exception can be largely eliminated.

Mr. Dwight also has some misgivings as to the ability of such synchronous condensers operating at very low excitation for supplying leading current at no-load. I do not think any such fear need exist—practically any synchronous motor with a proper damper winding will hold up the voltage on poorly regulated systems at no load and very small excitation.

I ask Mr. Dwight if in his table on page 1556 the power factor at the generating station has been taken into account in determining the size and cost of the two schemes. In one case it is given as 99 per cent, while in the other it is given as 89 per cent. This difference of 10 per cent in the kv-a. capacity will increase the cost for the constant voltage method, but it is a minor point in connection with the total saving incident to the system.

R. B. Williamson: Mr. Newbury's paper is an exceedingly valuable and interesting one, and particularly so to those engaged in the design of self-starting synchronous motors. The various oscillograms give a complete picture of the actions that take place during the different stages of starting and make many things plain which, while known to exist were not heretofore clearly understood. Some of the features brought out by Mr. Newbury were touched on during the discussion of these motors at the meeting of the Institute held in April, 1912, in Pittsburgh, and the present paper clears up a number of points brought up at that time.

Mr. Newbury's conclusions drawn as they are from the very complete set of oscillograms leave little room for discussion. Some of the results obtained show that this class of motor is capable of performances at starting and pulling into synchronism much beyond the limits usually considered possible.

As regards starting from rest, the difference noted between the torque developed with the rotor winding open and closed is considerably less than most machines that have come under my notice. However, this is something that depends very largely on the design of the machine, and I agree with Mr. Newbury that except in cases where a very high starting torque is desired and where a high-resistance squirrel cage is used, it is possible and preferable to start with the field short-circuited through the rheostat though it may be necessary to open the field circuit later in order to prevent locking at half speed. I understand that the machines tested by Mr. Newbury had a laminated rotor spider; in machines having a cast-steel or cast-iron spider, the voltage induced in the open field winding is considerably less than when the field structure is laminated throughout.

An important feature brought out is that it is not necessary to have two starting points, provided the most favorable procedure is adopted when starting; and the deductions drawn from the oscillograms show the methods of starting and amount of

excitation best suited to different starting conditions. Before the influence of field excitation on the momentary rush of current at change-over was discovered, there was considerable trouble with these motors due to tripping circuit breakers. The oscillograms show plainly why this was so.

To many who have not experimented with this class of motor it will appear surprising that Mr. Newbury was able to pull loads practically equal to full load into synchronism. However, this is quite possible, although the large current required to do it must not be lost sight of, and in many cases this would preclude the use of the synchronous motor on such large starting load, unless of moderate size or operated on large systems where the current at starting was not objectionable. Fortunately, however, in many of the largest applications it is possible to reduce the pull-in torque required to a fraction of full load so that the starting current can be kept down. For example, air compressors can be unloaded, and centrifugal pumps can often be started with the discharge valve closed. Many of the early self-starting motors were made from parts originally designed for alternators, and did not give the best starting performance possible; but with careful design along the well-established lines of squirrel cage induction motors, starting performances comparing favorably with the induction motor can be obtained.

Mr. Newbury's paper deals with motors of the salient pole type and it may be of interest to mention some tests recently made on a small turbo-generator run as a three-phase self-starting motor. There has been, at least among some engineers, the opinion that the pulling-in effect is due partly to the fact that the poles are sharply defined, and that a machine having a cylindrical rotor without projecting poles and with a distributed field winding would be deficient in pull-in torque. Some tests were made with a small 125-kv-a., 2300-volt, 31.2-ampere, 3600-rev.per. min. turbo-generator having a smooth cylindrical rotor with 36 slots uniformly spaced around the circumference. The retaining wedges for the coils were of brass, and made connections at each end with bronze end bells, thus forming a uniformly distributed squirrel-cage.

It was found that with the field circuit open, this machine started with 280 volts applied to the stator and came up to speed in 54 seconds while drawing a current of 67.8 amperes. That is, the motor started on approximately 12½ per cent voltage and 2.2 times full load current. The power factor at starting was between 45 and 50 per cent. With the field short-circuited, there was very little difference in the starting performance, the voltage and current being practically the same as before. Tests were also made with various resistances ranging from 0.9 ohm to 22.4 ohms in the field, but there was very little change noticeable in the starting performance.

Some tests were also made to determine the load that could be pulled in. With 1130 volts (about ½ voltage) applied to

stator and with a field current of 19 amperes, it was possible to pull in a load of 32 kw. or about 25½ per cent of the rated output. The stator current just before synchronizing was 40 amperes or 1.28 times full load. Since the torque may be taken as approximately proportional to the square of the applied voltage, it is seen that this machine would probably pull in nearly full load if thrown over to full voltage. This was not tried in these tests on account of the loading arrangements not being suitable, but it is evident that the round rotor motor can pull in loads comparable with those handled by the salient pole machine.

H. M. Hobart: I share Mr. Williamson's views, and I am hoping that Mr. Newbury's paper will rather stir things up and make people take a little new courage in approaching the subject of the design of synchronous motors. It has gotten into a terrible rut, it seems to me. This is partly due to the cause to which Mr. Williamson alluded. Matters have drifted into having the design of synchronous motors handled by the same departments that handle low-speed alternating-current generators. Any proposition to consider the design of synchronous motors along the lines of the design of induction motors has always been handicapped by the necessity of a change of hands, as to who should design it, and bring about the evolution of the synchronous motor into a decent machine. It is at present an absurd caricature of what it might be and the tantalizing part of it is that there are several perfectly serviceable methods ready and waiting to be used, but you cannot get anybody to look at these methods, or incorporate them in their designs, simply because they are following the old cut-and-dried methods, and everybody turns a deaf ear to any propositions for improvement.

Mr. Williamson alluded to some very interesting departures which he has had in hand and which it seems to me should offer much promise, but there are also other methods which would also serve to render the synchronous motor an admirable machine and make of it a machine which could be more widely used, for the reason that it will tend to decrease the price at which power can be provided to the consumer, in many cases, because you can run your synchronous motor with a leading power factor. That is a very important point indeed.

I believe that the synchronous motor can be used to great advantage in much smaller sizes than has heretofore been considered desirable, in sizes which will lap over into the field that has been generally held by common consent to belong to the induction motor. If only the synchronous motor could be designed by induction motor designers, working on the lines which have enabled them to see just what is needed for these starting and running-up conditions, the result would be for the good.

The induction motor has the fault that if you give it high starting torque, with the squirrel-cage variety, that will be accompanied by low efficiency and considerable heating. It must have high resistance in the squirrel-cage rotor, for the purpose

of giving the starting torque required in many special cases. This is an inherent characteristic of the motor. But in the case of the synchronous motor you can, in a sense, leave it behind when you synchronize the machine and have a highly efficient and cool-running machine for ordinary running, yet at the same time have a high starting torque, so that the synchronous motor, instead of being inferior in regard to its ability to have good starting torque characteristics, has an advantage over the induction motor in those respects. It ought to be associated in our minds as a characteristic of synchronous motors that they can be given *better* starting torque than induction motors, whereas we have just the other notion.

In reading over Mr. Dwight's paper, far too hurriedly, for so excellent a paper, it seems to me the nature of the results, and the careful calculations which he made, bring out much more strongly than they ever have heretofore been brought out, the advantages to be derived from this use of synchronous condensers in connection with long-distance transmission. The result is that the differences, expressed in percentages, are tremendous as regards extending the limitations. Why are we going to 100,000 and 150,000 volts? Because we have exhausted the possibilities of lower voltages in the matter of reaching out over wide areas and delivering energy at the limits of the system at a price which can compete with local plants. If, as Mr. Dwight's figures appear to show, you can, with a given voltage, if you operate on this principle, extend these limits 50 per cent, so that you can carry out at 100,000 volts, an undertaking in connection with which you would otherwise have to resort to 150,000 volts, you have just so far extended the limits, and when you are driven up to 150,000 volts, or higher, this further extension of the limits is still at hand.

As regards the amount of power transmitted, the distance to which it can be transmitted, and the price at which it can be delivered at a great distance, it would appear from Mr. Dwight's figures that the constant voltage method of working will lead to great extensions of the possibilities in connection with the electrical transmission of energy. It seems to me that the conclusions are very fairly and clearly stated, and that the paper is for this reason a very valuable one.

Lee Hagood: I have been very much interested in Mr. Dwight's paper. It struck me that the most interesting feature of it was that he could work out so many results and come to such valuable conclusions by such very simple methods.

A short time ago I was identified with the design of a system in which we were laying out a 110,000-volt transmission line, and our starting point which had to be settled was: what would be the size of our synchronous condensers. The necessity for this arose because our load was chiefly an inductive one, and we could not proceed with the design of the system until we settled upon the difference in voltage between the generating and receiving

stations at full load. Until this was settled, we were unable to fix the voltages and taps for the transformers and the kv-a. ratings to give our generators and transformers. Another point of considerable importance was the size of conductor. As the transmission line was very long, it was important, on account of expense, to use as small a conductor as was consistent with good engineering. All of these points revolve around the question of voltage difference maintained between the generating and receiving stations, because the power factor and efficiencies of the line have fixed relations depending upon the kilowatt load for a given voltage difference and line constants. The question of the size of synchronous condenser is dependent upon this and also upon the power factor of the load.

I note that Mr. Dwight does not take into consideration the charging current of the line. I think this can be neglected for lines under 60,000 volts, but I think for all long lines above this, it should be included.

(The lantern slides and explanations of them, included in Mr. Hagood's discussion, will not be reproduced here, as they were used in connection with a paper presented before the Los Angeles and the San Francisco Sections, entitled *Operation of Transmission Lines*. It is published in this volume, p. 855.)

N. E. Funk: Referring to Mr. Parker's paper, I wish to call attention to the fact that even though we consider raising the power factor from a low value to unity, which is the worst condition so far as cost is concerned that can be imposed upon a synchronous condenser installation, the cost balance will still be on the right side of the ledger, as the following table will show.

Load.	P. F. of load	P. F. of Line	Syn. motor capacity.	Gen. capacity	Cost of gen.	Cost of motors	Cost per kw. of load	Savings per kw. of load
100	80%	80%	0	137.5	$10,312.50	0	$103.125	
100	80%	100%	60	104.93	7,869.75	$600	84.69	$18.435
129	80%	100%	77.4	137.5	10,312.50	774	85.80	20.00
129	80%	80%	0	182.1	13,657.50	0	105.80	

The above table is based on a 10 per cent line drop in the first instance and the same line used in the other cases. Cost per kw., generators = $75, cost per kw., motors = $10. The first two lines show the saving in generator capacity by using synchronous motors. The last two lines show the increased cost of generators required without synchronous motors to load the generators in the first line with synchronous motors.

Mr. Parker says: "Where the synchronous quadrature demand can be made in excess of the lagging quadrature demand from induction motors, it then becomes desirable to put inductance in series with the feeder, thereby overcoming the drop due to the in-phase amperes operating in conjunction with the line

resistance." By doing this the drop is decreased, but at the expense of a lower power factor, which will increase the kv-a. capacity of the generators faster than the decrease in drop decreases it. The idea is that where a transmission problem involves the use of synchronous machines to control power factor it is much better to favor the generating station, as it is the most expensive part of the equipment.

M. T. Crawford: Mr. Dwight states that in commercial practise with short lines, constant voltage transmission is worth while merely on account of the improvement in service. In a system where the average load conditions are found, there are always a number of feeders supplying industrial power and railways in which a voltage variation of 10 per cent is within the limits of good service. For the remaining feeders supplying light and small power, automatic feeder regulators can be installed and operated at a much lower cost than the synchronous condenser installation for constant voltage operation. It might thus appear that where the lines are fairly short and no marked saving can be made by their increased carrying capacity, separate automatic regulation might generally be more economical, especially as it avoids increasing the amount of apparatus and complication of the high-tension system.

Henry W. Peck: An idea which may be of interest occurs to me, viz., that possibly we can use synchronous motor exciting apparatus to greater advantage at the distributing end of some of our lines than at the generating station end. In Schenectady, where we purchase 40-cycle power and transform it to 60-cycle, we have several small machines in the generating station which we practically never use, and as soon as I return home I intend to look up the matter as to whether or not we can use these motor-generator sets advantageously as synchronous condensers on some of our long feeders.

One line which I have particularly in mind supplies an amusement park about five miles (8 km.) out of the city, the line being about ten miles (16 km.) long. When the park is not being run we get reasonably good regulation on the line, but when the park is in operation we have a good many complaints regarding our service. I believe we could advantageously take some of our synchronous generating equipment and make better use for it at the end of the line. I realize in making this suggestion that the present machine would not be ideal for that service, but when you consider the scrap value of such a machine, which is all that you could get for it, it means the tying up of very little investment for the sake of this regulation. If this idea is not practicable and this plan will not apply I will be glad if some of the designing engineers will tell me why it will not apply.

F. C. Caldwell: What is the comparative effectiveness of synchronous machines, such as synchronous condensers, when running at full load, running at half load, and running light?

F. D. Newbury: I think that Mr. Caldwell's question can be best answered by reference to the familiar right-angle triangle

of which one side represents the energy load carried by the motor in any particular case; the side at right angles to this, represents the leading wattless kv-a. supplied to the supply line; and the resultant of these two represents the total kv-a. load on the motor. If the energy and wattless loads are equal, (representing the total load by 100 per cent), each will be equal to 71 per cent. Thus, if these two functions were performed by separate motors, the two motors would require a combined capacity of 142 per cent. If the ratio of energy load to the total load were smaller—say, 60 per cent—the wattless component would be 80 per cent to load the motor up to 100 per cent. Thus 140 per cent "service" is obtained as compared with 142 per cent in the previous example. It will be found that the maximum service will be obtained from a given motor when the energy and wattless components are equal—in other words, when the energy load is 71 per cent of the total. This, of course, is the same as 71 per cent power factor.

Burton McCollum: Mr. Dwight points out in a very effective manner some of the advantages that accrue from the use of synchronous condensers in connection with constant voltage transmission, particularly the operating advantages, and he also cites some rather remarkable economies, particularly where he gives some comparative cost data, but I believe that in most cases these economies are largely apparent only.

In the second comparison for the 100-mile (160.9-km.) transmission line he makes a comparison on a 54,000-kw. transmission, and reduces the efficiency of transmission from 95 per cent to 91 per cent, but by so doing he is able to bring about an economy of something like 26 per cent in the initial installation. Now, if we figure the money value of the increased energy loss that results, using the rather liberal line loss factor of 0.3., (the ratio of the average square to the maximum square) and taking one half a cent per kw-hr. for the value of the energy, we find it figures out at $27,500 a year as the value of the energy loss, which is more than 10 per cent of the saving that results in the line construction.

A similar statement can be made in regard to the first comparison, although the results are somewhat less marked. This statement would of course apply to a steam plant transmission line rather than a water power transmission. In the case of the water power plant the value of the energy lost would be less, but the line loss factor would usually be larger, which would partly offset the lower value of power.

I do not want to detract in any way from the importance of the paper by Mr. Dwight, because I regard it as an important development in engineering, but I feel that the advantages that are to be looked for are for the most part advantages in improved operating conditions rather than in increased economies.

H. B. Dwight: Mr. Parker's paper on the application of synchronous motors in the distribution of power in cities, shows

that this type of apparatus produces desirable economies and improvements in operating conditions in this class of work. As he points out, the supply company is benefited rather than the customers, and accordingly the latter must be compensated for installing the more expensive synchronous machines. He suggests making compensation by charging for the kilovolt-amperes supplied, thus influencing each customer to operate at all times as closely as possible to 100 per cent power factor.

Although it is evident that compensation must be made to secure the installation of synchronous motors, there are two objections to the above method of charging for electric power, namely, that the kilovolt-amperes are very difficult to meter, and that this method does not secure the best possible benefits from the synchronous motors according to the real needs of the supply company. The benefits may be of two kinds; first, reducing the kv-a. load on the generators, and second, reducing the cost of feeders by improving the voltage regulation. For the first, the synchronous motors should operate as strongly leading as possible at all times, but for reducing the necessary cost of feeders, which is often comparable to the cost of generators and which is also often increased by poor voltage regulation, adjustment of the synchronous motors is necessary. This is well accomplished by automatic regulators, as mentioned in Mr. Parker's paper. The saving in cost of feeders can also be made by installing a high-voltage transformer. Neither of these methods of operating the motors corresponds to keeping the customer's power factor at 100 per cent. It is accordingly better not to charge for the kilovolt-amperes, but to charge for the kilowatts, as usual, and to have a separate provision in the contract giving a bonus to the customer for operation of the motors either according to instructions from the company, or by automatic regulators.

Regarding the paper on constant-voltage transmission, Mr. Newbury, I believe, mentioned that for railway work the frequency of 60 cycles is being used to an increasing extent. This is true where alternating current is used to supply direct current railways, since the 60-cycle synchronous converter is now becoming more popular. But for single-phase and three-phase railways, the frequency of 25 cycles is used, owing to the characteristics of the motors.

The same speaker asked if allowance had been made for the ten per cent difference in the power factor of the generators in the 200-mile (321.8-km.) line. The item was not written down in the comparison as it would amount to only about $20,000. A more important item is the cost of energy for extra line losses with the constant-voltage system, as mentioned by Mr. McCollum. For a water-power plant, this item is equal to the cost of machinery to supply the extra losses at peak load. At $50 per kw. this amounts to about $200,000 for the 100-mile (160.9 km.) line which Mr. McCollum took up. Against this item, there

must be taken into account the two other items not put into the table because of their indefiniteness. These are the saving in the cost of land and the value of the improvement in service, and they balance fairly well the cost of power for extra losses. The purpose of the cost comparisons in the paper is to point out that for almost any installation it is worth while figuring up costs to see if synchronous condensers are not profitable.

The curves shown by Mr. Hagood were very interesting and I have just one small matter to bring out regarding them. The capacity of the synchronous condensers was plotted always as a straight line. You will notice in the chart, Fig. 5, of the constant-voltage paper, that the capacity of synchronous condensers required is a curved line, and its curvature puts a theoretical limit on the amount of power which can be sent over a transmission line. In the case considered of the 200-mile (321.8-km.) line, the limit is only about 25 per cent more than the amount of power assumed for full load. The curvature of that line is evidently worth figuring up in long distance work. It is a rather peculiar effect that there is this theoretical limit to the power capacity of a transmission line of a certain voltage, which cannot be overcome by synchronous condensers nor anything else.

Lee Hagood: I cannot prove these curves mathematically, but I have tried a number of them and found them all straight lines.

H. B. Dwight: I have no doubt that the points you have plotted, as you say, are correct, and as far as you have gone along the line, it is practically straight. But the indication in plotting a straight line is that unlimited power could be transmitted over the line if enough synchronous motors were added. The limit, however, is struck very soon by this theoretical consideration which will show up if you try to put 50 per cent more power over the transmission line. You would run into the limit with your calculations in the same way.

Lee Hagood: I do not agree with you.

J. C. Lincoln: I inquire of Mr. Newbury what the starting torque is when synchronizing on the three types of rotors shown on page 1514. The curve is interesting, and it appears that the starting torque of the rotor with the brass damper windings is at rather high resistance, which is much greater at any particular voltage than in the case of the starting torque at low resistance, and my question is, which is the type of rotor that will come in synchronism with the least amount of current? Is it the brass rotor or the low-resistance copper rotor?

F. D. Newbury: To answer Mr. Lincoln's question first; there are two entirely distinct actions to be considered—two entirely different sets of characteristics. The copper damper winding which shows the lowest torque at starting will of course have the lowest torque as long as the motor is operating as an induction motor. The torque at which a given motor will pull into synchronism depends on the torque that results in a certain

slip. There is a limiting slip, that may be one per cent or two per cent, beyond which the motor is incapable of pulling over from the highest induction motor speed into the true synchronous speed. Therefore the torque, that a given motor will pull in, will depend on the torque that can be pulled by the motor with a given slip. Therefore, the motor with the lowest resistance damper winding will carry the most load with this limiting slip, and consequently will pull into synchronism with the largest load. On the other hand the high resistance winding will develop the largest torque at the lowest speeds as in any induction motor.

J. C. Lincoln: If there was contained in the paper a complete speed-torque curve, would the torque of the lower resistance copper-wound rotor be greater or less at speeds just under synchronism than the torque of the higher resistance brass-wound rotor? It is very evident from the curve shown in Fig. 9 that at low speeds the brass-wound rotors have a very much higher torque than the low-resistance copper-wound rotors. It would seem to me that, at the higher speeds, just under synchronism, the lower resistance copper-wound rotor would have a higher torque than the higher resistance brass-wound rotor, and therefore that a synchronous motor provided with a lower resistance copper-wound rotor would pull into synchronism a larger load than the high resistance brass-wound rotor. I would like to ask the author of the paper if that is the case.

F. D. Newbury: The torque of the low-resistance rotor would be greatest at the highest speed at which the motor operates as an induction motor and will pull into synchronous speed.

J. C. Lincoln: That would amount to the same thing.

F. D. Newbury: Mr. Williamson spoke of the paper on the synchronous motor which was presented at the Pittsburgh meeting of the Institute last year. The admirable paper by Mr. Fechheimer was the starting-point of my own paper, since at that meeting the discussion was not at all favorable to starting with the field circuit closed. It may not indicate any change in the opinion of the members present, but simply indicate a change in audience, that the sentiment expressed at this meeting has been in the opposite direction.

As Mr. Williamson pointed out, I think the tests show that two starting voltages are not necessary, but I would qualify that in this way—that they are not necessary, provided proper adjustments are made, but proper adjustments always mean careful and skilful attention, so that the two starting taps are used and are justified for the larger motors, where the consequences of wrong operation would be quite serious.

Mr. Hobart has regretted the lack of attention that has been given to the wound-rotor distributed type of synchronous motor. I think that it is more a lack of results than lack of attention, and the reason for the lack of results is more fundamental than a difference of engineering department organization as Mr. Hobart

suggested. The real reason is brought out by the difference in the magnetizing current required by a well-designed induction motor and a well-designed synchronous motor. In an induction motor the magnetizing current is roughly 30 to 40 per cent of the armature current. In the synchronous motor the magnetizing ampere-turns should be at least one and a half to two times the armature ampere-turns. In order to obtain the necessary exciting ampere-turns on a round rotor synchronous motor a much larger rotor is required than for the salient pole type of synchronous motor or the round rotor type of induction motor. There is a good engineering reason, therefore, for the practically exclusive use of the salient pole type. The same conclusion is reached by a comparison of the weights and costs of salient pole and round rotor types of alternators. I think it is well known that the round rotor type of alternator ordinarily used for turbo-generators means a larger machine and a more expensive machine than the salient pole type and the round rotor type is used because it is the only type sufficiently strong mechanically. The same point was well borne out by comparisons recently made on some 10,000-kilovolt-ampere, 600-rev. per min. waterwheel generators, where the cost of the salient pole type was found to be approximately 50 per cent less than the round rotor type.

M. O. Dell Plain: I believe that the possible advantage to be gained by the average central station through a general use of synchronous motors instead of induction motors on its lines is largely offset by the greatly increased number of motor trouble complaints.

The advantage to be gained by the consumer is a very material one in cases where the central station penalizes a low power factor. This advantage, however, is also offset if the current charge is based directly on the demand. In such cases the present lack of a suitable demand meter results in considering the highest phase kv-a. reading as being the actual demand, and an unbalanced load being the usual condition, the synchronous polyphase load does not produce its fullest effect in lowering the actual charge.

The development of a reliable and inexpensive kilovolt-ampere demand meter would probably eliminate this objection.

Henry W. Peck: I have made a memorandum of two or three points which I will answer. The quality of the service is oftentimes more important than a very slight advantage in maintaining unity power factor at the station. It is not for the sake of the power factor primarily, that Mr. Parker suggests the use of synchronous condensers, but to maintain the service which we are giving to our customers.

Another suggestion was made that the synchronous condenser was in competition with the high-tension transformer. An operating man does not like to see his system separated into different voltages, 2300 volts on one part, 6600 volts on another part, and 13,000 volts on another part. From the opera-

ting point of view it is much simpler to have the synchronous condenser than to step up certain portions of the line and have a great variety of transformers which you must carry in stock so as to be able to supply your customers with these transformers when they want them.

Referring to Mr. Dell Plain's remarks, it is manifestly impossible to put a synchronous motor in every and any installation, regardless of the character of the plant and the man who is running it. In the case cited by Mr. Parker where they use the synchronous motors for pumping, refrigerating plants and similar purposes, they have operating men who are certainly of as high a class as any men we have in our own stations and who can be trained to operate the synchronous motors satisfactorily.

We must consider the economy of such an installation from the point of view of both the customer and the company. The customer must decide if the saving, due to the lower rate for power, is sufficient to warrant him in installing these appliances in his power plant, granting that they are not quite as simple and convenient as the induction motor. The company must decide if the saving and improved service incident to the installation of these appliances are worth the expense represented by the decreased rate for power and by the assumption of such part of the first cost of the machine as is represented by the excess capacity required to handle the wattless load.

As regards metering the kilovolt-amperes, I know that it has been done in one installation which was put in under Mr. Parker's direction, using two meters, a graphic voltmeter and a graphic ammeter. The installation in which this meter was placed was of 600-h.p. capacity, and the cost of these meters, while prohibitive on smaller installations, was by no means prohibitive for one of such large size. If the phase voltages were perfectly balanced there would be no difference in the current in the different legs. Measurements were taken at this installation and it was found that the difference in voltage and current in the different legs was negligible.

N. E. Funk: I did not mean to leave the impression that poor service was to be furnished so that the power station might enjoy the benefits of a high power factor, by any means. What I meant to convey was, that it was the best policy to attempt to get unity power factor rather than leading power factor, which is as bad in so far as generator capacity is concerned as a lagging power factor. In following out this manner of design it is not necessary for the voltage at the receiving end of the line to vary any more than if the voltage were the same at both ends. There are various means of correcting voltage besides that of synchronous condensers, and if it is not possible to favor the generating station and get the proper voltage at the receiver this receiver voltage may be corrected by, say, induction regulators, and the synchronous motors used to annul the lagging component of the load. The thing I had in mind most particularly was the

fact that it was better policy, on account of favoring the generating station and apparatus, which is the most expensive part of the system, to strive toward obtaining unity power factor on the generating station rather than calculating the line for a given voltage at the receiving end and allowing the power factor at the generating station to come what it may.

C. P. Steinmetz: The two papers on synchronous motors are very interesting to me, as they give much additional information regarding the usefulness of the synchronous motor as an element of the electrical system, particularly Mr. Newbury's paper with regard to the starting characteristics of the synchronous motor. Synchronous motors, synchronous converters, and synchronous condensers have now been used extensively for over 20 years, and their use is very rapidly increasing. Most of these machines are self-starting, starting from rest with their own power, but still I believe there are a few engineers who doubt the self-starting characteristics of the synchronous motor and consider this as the main disadvantage of the synchronous motor.

The fact is, as brought out by these papers, that the modern synchronous motor, and also its prototypes, are very well able to start from rest and run up to speed and carry considerable load up to speed. They, indeed, take a large current in starting and during acceleration, about as much as the large highly efficient induction motors. The induction motor has never been questioned as to its ability in starting; but the synchronous motor is fully as well self-starting, and sometimes it takes more current and sometimes less current than the squirrel-cage induction motor, as, indeed, it is an induction motor. It differs in these starting characteristics, from the standpoint of the well-known squirrel-cage induction motor of large size, only in the proportioning of the parts. The starting characteristics of the induction motors have been limited by the proportioning of the parts required for getting efficient running, mainly for the purpose of getting high efficiency, high power factor, or low exciting current.

These limitations are not questioned in the induction motor characteristics of the synchronous motor, because the synchronous motor is not expected to operate at speed as an induction motor. Therefore, whatever power factor and efficiency it might have when running at speed as induction motor is entirely immaterial, and therefore in proportioning the induction motor parts of the synchronous motor we are more unrestricted, in choosing those proportions which are capable of giving good starting characteristics, than we are in the large induction motor. That means in many cases it is possible to give to the synchronous motor better starting characteristics than to a large squirrel-cage induction motor. I pointed out some of these things in a previous discussion, for instance, that in the synchronous motor we may have, considering it as an induction motor, an exciting

current of 100 per cent or more without its having any detrimental effect. In the induction motor obviously such an exciting current would make it commercially inoperative, the reason being, at that time, under the conditions where the synchronous motor acts as an induction motor in starting, the energy current for acceleration is so large and the impedance current is so large that the exciting current does not cut any figures. It is negligible, no matter how much it would be in percentage compared with full load current.

The main differences in the proportioning of the induction motor part of the synchronous motor compared with the induction motor are three. First, the synchronous motor does not have uniform magnetic reluctance in all directions of the rotor, it is minimum in the direction of the field poles, and maximum at right angles thereto while the induction motor has uniform reluctance all around. This is a disadvantage in regard to the starting of the synchronous motor as an induction motor, since it tends to a lack of uniformity of the torque with the relative position, and thereby also tends to low torque points, that is to a tendency of sticking, as it is called, at intermediate speeds, more particularly at half synchronism. Second, the synchronous motor has a very large air gap compared to the air gap used in the induction motor. The induction motor, to get good power factor, low exciting current, must have as small air gap as mechanical construction permits. In the case of the synchronous motor the power factor and the running on light current do not depend on the length of the air gap. Therefore the air gap, in the case of the synchronous motor, is chosen in accordance with very conservative mechanical and other considerations. The large air gap has an advantage in starting, in so far as it tends to give a uniformity of torque. Third, the secondary winding of the synchronous motor, compared with that of the induction motor, is of much higher resistance, which again is an advantage in starting, so, you see, of the three main characteristic differences in the proportioning of the induction motor part of the synchronous motor, one is against but the other two are in favor of high starting torque and the result is that the synchronous motor really starts better than a large high efficiency squirrel-cage induction motor.

The oscillograms shown in Mr. Newbury's paper are extremely interesting in giving the starting characteristics, but from these oscillograms you can see there are many other things which the limitation of space did not allow Mr. Newbury to show. If you look at them you see this more particularly, in the case of the oscillograms of a current, the amplitude of the current, the periodic rise and fall. You see the meaning of that—it is due to the varying magnetic reluctance with the position; maximum current corresponds to maximum reluctance, minimum current to minimum reluctance. Hence the distance from current maximum to current maximum corresponds to the dis-

tance moved by the rotor from one maximum reluctance point to another maximum reluctance point, which means the distance of half a field pole or multiples thereof, or the slip of half a field pole or multiples thereof. That means the space moved through but the frequency of the oscillograms gives the time, and therefore you see from these oscillograms that you can get, from the distance moved by the rotor and the time of motion, the speed-time curve during acceleration, and from the speed-time curve you get the acceleration-time curve, and therefore since acceleration gives you the torque, relatively, or when considering the momentum of the moving mass, then absolutely, you get the torque-speed curve. That means a variation of the torque of the machine from standstill up to synchronism. All the characteristic curves of motion you get from these oscillograms, curves which in the induction motor are difficult to get, because in the induction motor the speed range near maximum torque, is unstable, and characteristics of that range can be derived mainly by connecting the motor with a generator which feeds a direct current motor connected to constant speed shafting and varying the field excitation of the motor which checks the output. This is well known and has many times been described, and in this way you can hold the induction motor at any point of speed, stable or unstable, above or below synchronism, and you can get the complete torque characteristics. The oscillograms of the synchronous motor permit you to arrive at a very definite understanding of the speed-torque characteristics, which in the induction motor you might get, possibly, an exploring winding on the squirrel-cage.

Looking at these oscillograms, you see a number of characteristics which are incidentally mentioned. If you take curve Fig. 2, at the end of the first oscillogram, you see a number of waves with a high and low amplitude alternating for a considerable number of periods there. Apparently the speed was practically constant, which meant a low torque point there, where the motor accelerated slowly, because after a considerable number of cycles there was no acceleration or little acceleration. That apparently corresponds to one-quarter synchronous speed, and later on at about two-thirds the distance of the second curve from the bottom of the page, there was a very large number of cycles where the amplitude is constant, where the machine moved from maximum reluctance point to maximum reluctance point, during one cycle or during half a cycle. During half a cycle it progressed half a field pole. That apparently is half synchronous speed where it tends to drop off a little. The next curve is still exaggerated, but much less prominent at the three-quarter synchronous point, so that if you would construct from the oscillogram the speed-torque characteristic, you would probably be required to introduce a considerable drop in the torque at half synchronism, a moderate drop of torque at one-quarter synchronism, and a further moderate drop of torque at

three-quarters synchronism. This is at the low voltage starting. At higher voltage starting that phenomenon is not so marked, but these oscillograms allow you to study the acceleration curve of the synchronous motor much more closely and control it much better than in the case of the induction motors, where it is more difficult to determine all these characteristics of intermediate speed. We thus see that, as an engineering problem, when it is necessary to provide high efficiency synchronous motors with good starting characteristics what we have really is a much more simple problem than in the case of the high efficiency induction motor. and in my opinion the large synchronous motor is really one of the most important, and most useful elements of the electric system, more so than the induction motor, because instead of spoiling the power factor it may be made to improve the power factor, and instead of interfering with the regulation, making the voltage vary more with the change of load, it controls, or permits the control of the voltage, or acts automatically without any control, by establishing a fixed voltage point due to its excitation. The synchronous motor tends to hold the voltage more nearly constant than the non-inductive load. Many engineers do not yet realize the usefulness and value of a synchronous machine as an element in the electrical system, and therefore I very much appreciate these papers, since they give additional information and undoubtedly will tend to give the synchronous motor a still wider application than it has today. The synchronous motor will naturally include the synchronous converter and the synchronous condenser.

W. L. Merrill: I desire to ask Dr. Steinmetz a question in connection with his discussion on synchronous motors, and that is, why he compared the large synchronous condensers or synchronous motors with squirrel-cage induction motors. It has been my experience in such applications where the question has arisen as to whether synchronous motors or induction motors should be used the squirrel cage motor would not even be considered; and it has been the custom always to supply wound rotor collector-ring type of motors in the majority of cases where practically any starting requirements were to be met. In some cases, however, where synchronous motors have been installed to do the work that is successfully being done by wound rotor motors, the operation of the synchronous motors compares favorably with the operation of a fuse after it is blown. I see no reason for comparing the synchronous motor with the squirrel cage induction motor for ordinary industrial applications.

R. B. Williamson: In regard to the point brought up by Mr. Newbury about the wound-rotor type of motor, my idea was not to recommend that type of motor in preference to the salient pole type. The experiment was tried simply to find out if that sort of motor could be started up equally well. Motors of this type might occasionally be used for high speed work. For ordinary service at moderate speeds they would have no material advantage and would be larger for a given output.

F. D. Newbury: I wish to thank Dr. Steinmetz for his contribution to the discussion, particularly, because his discussion brought out a number of points I hoped would be brought out; and I am free to confess that they were not included in the paper for other reasons than lack of space and time, as Dr. Steinmetz was kind enough to suggest.

There is one point in particular I have not been able to understand myself; possibly Dr. Steinmetz can explain it either now or after he has studied the matter a little. Figs. 28 and 29 show exactly the same conditions, but there is a very marked difference in the amplitude of the armature current and field current changes.

C. P. Steinmetz: I wish to think the matter over a little more and cannot give an answer now, but in regard to the former question, as to why I compared the synchronous motor with the squirrel-cage induction motor, the reason was that, when the synchronous motor starts, it starts as a squirrel-cage induction motor, since it is provided with a squirrel-cage, so we would naturally compare that with the squirrel-cage induction motor.

We all realize that there are very many motor applications where we need frequent starting at heavy torque and where we, therefore use the collector-ring induction motor. These applications naturally would not, as a rule, be met by the synchronous motor but in the majority of cases the squirrel-cage induction motor is used and therefore I compared that motor with the synchronous motor. It does not mean that we can use a synchronous motor in every place. The induction motor with collector rings and rheostat armature control has its legitimate and very important field. We may say that since the synchronous motor starts as an induction motor instead of providing a squirrel-cage, a regular winding could be used with a rheostat and improve the starting of the synchronous motor and such was the point I made.

I remember the first big synchronous motor with which I had anything to do, that was in 1893, somewhere on the Pacific coast. The motor is still running. It had a three-phase pole face winding, each winding brought out to a switch, in which a rheostat was connected for starting, but that has never been done since, because there was no need for this complication; and in all the conditions where the synchronous motor was used it was considered all right to start as a high-resistance squirrel-cage motor. That might possibly be done in the case of the synchronous motor by giving it collector rings and the wire-wound induction motor winding. The objection to that is it means a winding which is used only in starting not in running, and that is a complication. If the winding is simple, as in the case of the squirrel-cage motor, which incidentally acts as an amortisseur winding—a damper winding when running at synchronism, —then it is favorable, but it is hardly justifiable in most cases, to go to the complication of an external rheostat, but rather to

use an induction motor with collector rings and rheostat, except in those cases, which may occur, where the synchronous motor is decidedly preferable. I do not recall any cases like this.

J. C. Lincoln: I would like to ask what is Mr. Newbury's experience with reference to the call for high starting torque at low speeds and high starting torque at near synchronous speeds. It happens my experience has been only where we had trouble when it was due to the fact that we had to have pretty high speeds near synchronism, but judging from the paper, and from the curves which are very instructive, I would infer Mr. Newbury's experience has been in cases where high torque was required in starting, and I ask what his experience is as to the ordinary requirements of starting torque, whether a high starting torque is required at starting or near synchronous speed?

F. D. Newbury: Whether the required starting torque is greatest at standstill or synchronous speed depends on the application. The majority of synchronous motors is used in motor generator sets where the largest torque is required at standstill. This may be considerable, as much as 50 per cent, in some cases, of full load torque. In the case of pumps and fans and air compressors, the highest torque is usually required near synchronous speed. In the case of fans it is very hard to shut off the air supply sufficiently so that the torque at full speed is not very near the full load torque of the motor. In the case of pumps where a by-pass can be used, the torque at synchronous speed is considerably reduced. In the case of air compressors, the bulk of the trouble has been at pull-in, and I imagine the absence of trouble in many cases has been due to the fact that the motor was pulled in on full voltage and not starting voltage. Probably the bulk of the synchronous motors have been used for motor generators sets, where the starting torque is the greatest, so that quantitatively the bulk of the trouble has been at standstill.

J. C. Lincoln: With a motor-generator set, would you use a low-resistance winding on the motor?

F. D. Newbury: Not necessarily. Many and perhaps the majority are now built with the brass or high-resistance squirrel-cage windings, illustrating the point Mr. Hobart and Dr. Steinmetz made, that it is possible to obtain the good starting performance of the high resistance secondary with the synchronous motor while it is not possible with the squirrel-cage induction motor. With steam- or water-driven generators now generally used there is little necessity for low-resistance amortisseur windings for prevention of hunting.

H. H. Dewey: Mr. Newbury implied that in the case of large, slow-speed synchronous motors, having a large number of poles, it is a difficult matter to obtain high torque during synchronism. Do I understand that it is harder to obtain it with a machine of this kind than with a high-speed machine having a smaller number of poles, and if so, to what does he attribute the difference?

F. D. Newbury: It is decidedly more difficult to get high starting torque at pull-in, as expressed in percentage of motor output, with the larger number of poles, and in the case of slow motors for air compressors the figure which has been more or less standardized by the compressor manufacturer's requirements, and also by tests, is about 15 per cent; that is, the motors will develop 15 per cent of their normal torque at synchronous speed. I have one installation in mind where they would just pull in, and the tests on the test floor show just about 15 per cent pull in torque. With slow-speed, two, four, and six-pole motors, used for fans, it is not difficult to pull in at practically full load torque, if you disregard the starting torque and current. The reason for this difference is rather intimately connected with the proportions of the two machines.

H. M. Hobart: For a long time salient stator poles were used for very high speed generators, but now I think there is a fairly universal agreement that the windings should be distributed, although it is only comparatively recently that there was any general agreement on that point. Previously the salient pole was strongly advocated for even very high speeds. I feel that there should be a closer analysis of the differences in the construction and of the respective fields of usefulness of synchronous motors and induction motors. If the synchronous motor is to be developed on progressive lines the work must be entrusted to those who are accustomed to induction motor design.

J. H. Wilson: The question has been brought up of the pulling-in effect with a high resistance motor. I may mention two cases I had recently to do with, where a 2400-h.p. synchronous motor was connected to some grinding stones for grinding pulp. The grinder in question was of a comparatively new type, where the wood is piled in the hopper, twelve cords of wood pressing on the stones at all times. This particular motor had a high resistance it had a squirrel-cage winding. I have no way of finding out what the pull-in torque was, but it must have been considerable, because there was always a large amount of wood pressing down on the stone, each stone taking about 1200 h.p. That motor would start up on 1¾ to 2 per cent full load current on half the line voltage, and seemed to pull into step without trouble, so that the high resistance winding at or near synchronism must have given fairly high torque.

C. P. Steinmetz: Regarding the pull-in torque, I wish to draw attention to the necessity of some further study of this matter. The phenomenon in the synchronous motor pulling in to synchronism is not fully realized by all engineers. It is really not so much a question of the load which is to be pulled in but a question of momentum. A synchronous motor may have difficulty in pulling into synchronism while accelerating without any load, while it may pull in nicely without any difficulty at full load, because when pulling in it means it has to jump from the slip given by the induction motor into synchronism, and in

that very short period it has to accelerate the momentum. The acceleration of the momentum is usually very much poorer than the actual load, so that you will find, when studying the pulling in of a synchronous motor, especially a high-speed motor connected to high-momentum apparatus, that the question of load or low load makes practically no difference, or very little difference. What we have to consider in the pulling-in characteristic of the synchronous motor is the momentum which has to be pulled into step, much more than the actual drag or torque.

F. D. Newbury: I do not wish to leave the discussion of round type versus salient type motors where it stands. There is not as much difference between Mr. Williamson and myself as might appear. I still hold to the point that it is a question of cost, and that is a hard question to overcome unless you can overcome it in the direction of a reduction of cost. I do not see how, from theoretical considerations, you can do that. Maybe I am mistaken, but I cannot see it.

There are others, notably Mr. Foster, who have had experience along these lines, and I would like to know from him and others, whether their experience has been the same as mine; that the salient pole type for a given output can be built more cheaply than the round rotor type?

I am entirely in agreement with what Mr. Williamson said in regard to the performance of the round rotor type. There is nothing against its performance; in fact, it has very decided advantages, as Mr. Williamson pointed out; there is uniformity of reluctance so that there is a uniformity of torque in the rotor; the starting performance of the phase-wound induction motor can be obtained by inserting resistance in the external exciting circuit; other decided advantages have led designers to investigate it thoroughly. If my conclusions are wrong, I would be glad to be corrected.

Wm. J. Foster: My experience agrees entirely with Mr. Newbury. That matter has been investigated in a number of cases during my experience of 20 years or more. I think the first synchronous motor I had anything to do with was built with pole faces 85 or 90 per cent of the pole arc, as against the ordinary 65 per cent of the generator. Much of the investigation made along that line, with regard to the design of the synchronous motor, is based on using stock parts of induction motors, since we have the benefit of the cheaper production, due to stock parts, and can easily make, the nesessary modifications in the rotor, with the increased air gap, etc. It has been my experience that we have never been able to work out that type of motor in competition with the salient pole in any size in which synchronous motors are called for. In very small motors, it is often a profitable thing, because there is not demand enough to warrant the development of an entire new salient pole machine. Hence the synchronous motor can be best built from standard induction motor parts in very small sizes.

As to the matter of the characteristics, I am sorry I have not exact data on the subject, but as far as my experience goes it has been in favor of the round rotor, that is, in returns that one gets for the input.

H. M. Hobart: People are usually willing to pay more for a good thing than for a bad thing, if only they can get the good thing.

W. J. Foster: I want to know in what respect it is a good thing as compared with the present motor. Why do you call one good and the other bad?

H. M. Hobart: I call it good because it starts with high torque and runs rapidly up to synchronism with good torque all the way through. These are not characteristics of synchronous motors as at present designed.

Wm. J. Foster: I have built and operated a number of motors of the wound rotor type, but I cannot agree with that statement. It is a question of how to adjust things with relation to the torque, and that is a serious drawback in the synchronous motor. It is right there where investigation has been going on quite actively in the last two or three years as to how to increase the torque.

R. B. Williamson: It seems to me the only reason for building synchronous motors with round rotors is the same reason for which we build generators with round rotors. It is a question of speed. To design a motor for, say, 3600 rev. per min., we would have to use a mechanical construction the same as for a turbo-generator; but for ordinary speeds where we would use a salient pole construction for a generator I should say by all means to use it for the synchronous motor. I do not think there are any great differences in the characteristics; the only thing I had in mind was the question of overcoming the mechanical difficulties at high speed.

W. L. Merrill: The principal point I wanted to bring out by asking Dr. Steinmetz the question I did is that the author of one of the papers appeared to be advocating loading up the central station lines with synchronous motors to the value of 40 or 60 per cent of their total load. My experience in industrial work is that possibly one or two per cent of the industrial applications of motors, with the present type of synchronous motor which we have, could be handled by synchronous motors, and I was afraid from the glowing comparison which Dr. Steinmetz made of the synchronous motor and induction motor that the impression might be gained that they were interchangeable, when as a matter of fact in the sizes which he was discussing no one would consider the question of a squirrel-cage motor any way. If we could get large synchronous motors, involving the characteristics of the form wound induction motors, it would not only be possible, but probable, that the central stations could go to 40 per cent of the total loads with synchronous apparatus.

Wm. J. Foster: I wish to say in connection with the point brought up by Mr. Hobart that if you put in an external resistance with a definite wound rotor, and make use of external resistances, you get excellent results, as far as starting torque goes. You can then cut out the external resistance and switch the excitation on two phases of the rotor winding, leaving the third phase idle, or use one phase against the other two for excitation.

H. M. Hobart: In my first remarks I said there were various ways of improving the motors which were quite available and valuable, but that no one wanted to use them, but I did not go into the question of what those ways were. They related to this question of getting a high torque not only at the moment of starting, but a high torque right straight through into synchronism. I did not feel that it devolved on me to go into the details of these methods on this occasion, since I have already published descriptions* of them. It is an interesting field to which little attention has been given. These methods will be widely used in the future. At present they are opposed in accordance with those general principles always acting when new ideas of value are first brought to attention.

C. P. Steinmetz: I do not think I am prepared to discuss off-hand the last subject which was brought up. We all realize what we have in the synchronous motor is the induction motor start, and also in the starting of the squirrel-cage, as squirrel-cage that is, high resistance in starting and decreasing resistance to a very low resistance at running, and that decrease should be as simple as possible.

In regard to the difference between the definite pole rotor and the uniform reluctance rotor, the main differences in my mind are that the definite pole rotor gives a less uniform starting torque, and if in starting we must consider the momentum torque, the definite pole rotor is inferior in starting, other things being the same, than is the uniform reluctance rotor. Furthermore, the definite pole rotor shows a drop in torque at fractions of synchronism, a certain amount at half synchronism, and less at quarter synchronism, more than the uniform reluctance rotor, which latter very often does not show a drop in the torque curve at all. On the other hand, the definite pole rotor drops into step easier, because it has that additional torque, the tendency of the magnetic lock, therefore in dropping into synchronism the definite pole rotor has the advantage.

At the moment of starting, the synchronous motor of today has ample torque to start any load which it will carry. However, the stopping off at half speed has been a very decided disadvantage in former times in the synchronous motor, but with the introduction of the fairly well distributed squirrel-cage winding, even with the winding local only through a wide field pole,

*See pp. 202 to 212 of "Design of Polyphase Generators and Motors", by H. M. Hobart.

that difficulty has practically vanished, so that as it stands today, on the average there is very little to choose between the definite pole rotor, and the uniform reluctance rotor. You cannot say they are exactly alike, the one is better in pulling in and the other is better in acceleration, but after all, that is a question of the nature of the load, and also a question as to how much the one advantage or the other is worth under the greater cost of the construction, or whether it is not worth anything at all. It is really like most engineering problems, an economic question between the engineering design and the requirements of service, and the cost of the apparatus; but in the last five or ten years the advantage in development has been largely in improving the starting condition and the fraction synchronous condition, that is, reducing and eliminating the disadvantage of the definite pole construction, so that today the definite pole construction really has practically no disadvantage as a synchronous motor over the uniform reluctance type. Today indeed in the synchronous motor, that field in which there is the least known or available in the literature, are the phenomena of pulling into step, and as you have heard from Mr. Foster a large amount of investigating work is being carried on in this direction, and I hope Mr. Foster will be able, at some of the future meetings, to give us some additional information of the phenomena occurring in the synchronous motor in that range of speed where it is not an induction motor any more, and where it is not yet a synchronous motor.

C. J. Fechheimer (by letter): The many oscillograms in Mr. Newbury's paper convey to our minds an unusually clear picture of the phenomena from standstill to synchronism, of the transients produced by the varying reluctance of the magnetic circuit due to the projecting poles, and those caused by temporary changes when the connections are altered. Inasmuch as the physical conception of a phenomenon frequently is of more importance than the mathematical, especially to the engineer or student who does not design the apparatus, the graphical oscillograph records are of great value.

Mr. Newbury states: "These facts show the desirability of starting synchronous motors with the field circuit closed (and so eliminating the high voltage from the field winding and the switchboard), except in special cases where unusually high initial starting torque is required. For such applications a high resistance damper winding is necessary, the benefits of which in producing torque would be largely nullified by the closed field of circuit. In such special applications, however, care must be taken to insure that the insulation of the entire field circuit will withstand the resulting voltage." This statement applies to motors with rotors equipped with squirrel cage windings and laminated poles. Mr. Newbury has not commented at all on synchronous motors with solid poles. We wish to call attention to the very desirable effects which can be produced

with solid pole rotors in which eddy currents are crowded into thin shells toward the surfaces, (the well-known skin effect phenomenon), whereby the starting torque is increased, whereas the number of inter-linkages of flux with the field turns is reduced, with the result that the induced voltage in the field coils is lowered.

We give below some data from actual solid pole machines which were available for the tests. From them it will be seen that the induced voltage with solid poles is small as compared with that obtained with laminated poles in which the squirrel cage construction is embodied. Instances of these latter are cited in Mr. Newbury's paper. We have taken as a basis of comparison the induced voltage with a torque of 30 per cent of normal full load torque, this value being as large as is usually demanded of synchronous motors at starting.

Rating	D-C. exciting voltage	Rotor voltage for 30% torque
2000-kv-a. 11,000-volt three-phase 50-cycle 600 rev. per min.	125	1690
180-kv-a. 2300-volt three-phase 60-cycle 150 rev. per min.	125	1790
350-h. p. 2300-volt three-phase 60-cycle 257 rev. per min.	250	2610
50-kv-a. 240-volt three-phase 60-cycle 1200 rev. per min.	125	1440
100-kv-a. 240-volt two-phase 60-cycle 257 rev. per min.	125	1230
150-kv-a. 275-volt three-phase 60-cycle 900 rev. per min.	125	427

We do not favor short-circuiting of the field coils at starting, since, for a given starting torque, not only is the line current increased thereby, but there is a possibility of the rotor refusing to accelerate beyond half speed unless the field circuit is opened. As stated by Mr. Newbury, and also in my reply to the discussion of my paper on *Self-Starting Synchronous Motors**, the rheostat resistance is entirely inadequate in assisting toward the reduction of line current for a given torque at the instant of starting. Motors with solid rotors have been built successfully for a number of years, and so far as we are aware, all of them are started with the field circuit open, the induced voltage in no case being prohibitive, no disastrous results having come to our attention as a result of the induced voltage.

It is interesting to note that with the solid pole construction, the torque is not proportional to the second power of the voltage, as is generally assumed, but to a slightly higher power, about 2.1 to 2.5 Similarly, the other quantities vary in a different manner than generally assumed. For example, in a certain 100-kv-a. solid rotor synchronous motor, the following relations were found by plotting results on logarithmic cross-section paper:

1. Torque varied as 2.5 power of voltage.
2. Torque varied as 1.73 power of current.
3. Current varied as 1.38 power of voltage.

*Trans. A. I. E. E., Vol. XXXI, 1912, p. 529.

4. Power input varied as 2.53 power of voltage.
5. Torque varied as 1.05 power of kilovolt-ampere input.
6. Kilowatt input varied as 1.05 power of kilovolt-ampere input.
7. Torque varied as the first power of kilowatt input to rotor.

A comparison of the above relations will reveal their consistency.

We believe that the departures indicated above from what would seem to be the most rational laws are due chiefly to the increased crowding of eddy currents into the shells of the rotor surfaces as the current is increased; thus the reactance of the eddy current paths is reduced, the current is proportionately increased, the power factor is slightly increased, etc. There are advantages in these relations, among them being that they result in a not inconsiderable gain in torque for a given increment of voltage, especially when the demand for such torque is greater than was first anticipated.

At first thought it may appear that the starting characteristics with the solid construction are predicted only with great difficulty due to the uncertainty of the laws which eddy currents follow. We would therefore call attention to the method given in my paper on this subject, and state at this time that we have been using this method for about three years with great success. We have recently modified the method so as to include exponents other than generally assumed, such as indicated above. With these modifications our method is substantially the same as previously described. In fact we believe that greater accuracy in the prediction of starting characteristics can be secured with the solid construction than with the laminated squirrel cage construction, there being less uncertainties in the former than in the latter.

The above is not intended to be more than a partial comparison of solid and laminated pole squirrel cage rotors.

It is now generally conceded, that insofar as the current taken when breaking loose from rest is concerned, the air gap should not be made smaller than would be best suited for the motor after it comes into synchronism and is excited in the ordinary manner. I wish to call attention, however, to my statement given in reply to the discussion of my paper previously referred to: "When operating at synchronous speed without direct-current excitation the current drawn from the line depends almost wholly upon the magnetomotive force required to force the flux across the air gap." From this point of view it will be seen that the effect of the air gap upon line current may be of considerable importance.

In Fig. 7, Mr. Newbury shows that the current after synchronism is less than at any time during acceleration. This would imply that the air gap is small, since as stated above, the air gap reluctance plays the chief part in the current taken after the machine locks into synchronism with no direct-current

excitation. In the various speed-torque curves shown in my paper, the current after locking into synchronism is somewhat greater than just before synchronism is reached. If a synchronous motor is designed to give double torque for pull out and is intended for unity power factor operation, the air gap will generally be of sufficient length to cause the current after locking into step to be greater than at about 95 per cent of synchronism. On the other hand, if the motor is designed with a small air gap and is intended to operate with leading power factor for balancing some of the lagging current in a system, the air gap may be so short that the current flowing when the motor is in synchronism without any direct current excitation is less than at any point during acceleration.

Mr. Newbury starts his synchronous motor on fractional voltage and excites the fields before throwing over to full voltage. He states: "The armature circuit is momentarily opened by throwing from the low voltage to the high voltage and current drops to zero during this interval." If the circuit is to be opened and then closed, his method might be a desirable one in cases where stored energy in the rotating parts is high, frictional torque comparatively small and the mechanical angle between adjacent poles comparatively large, such as would be the case, for example, with synchronous motor-generator sets. On the other hand, were the synchronous motor to drive a reciprocating air compressor, the motor operating at a small angular velocity, the frictional resistance being rather high, the mechanical angle between poles small and the stored energy small, the rotor may change its phase position appreciably during this transitional stage. When full voltage is then applied, there is a possibility of setting up rather high mechanical forces and of causing a momentary large current rush. Hence, we may conceive of trouble ensuing in cases of this kind. It may then be best to throw on full voltage before applying direct-current excitation. If the circuit is kept closed during the transition from fractional to full voltage, we believe it best in all cases to excite the fields on fractional voltage, so as to reduce to a minimum the current which would flow after full voltage is applied.

It is usually undesirable to apply as much as unity power factor exciting current in order to cause the motor to lock into synchronism provided synchronous speed cannot be obtained without the application of such current. In Figs. 11, 12 and 13 and accompanying description in my paper referred to above, it is shown that there is a critical value of excitation for each speed which will give maximum torque, beyond which the torque drops off, but the current in the stator increases. A knowledge of this characteristic may prove valuable to the operator who has had difficulty in causing his motor to lock into synchronism, or finds the current drawn excessive for his supply system.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 26, 1913.

Copyright, 1913. By A. I. E. E.

STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS

BY H. G. STOTT AND W. S. GORSUCH

The need of some uniform method of accounting for the determination of the cost of power in steam plants has been long felt. The subject, however, seems to have been allowed to drift along without reaching any very definite conclusion, with the natural result that there are numerous forms in use today. These forms are founded upon assumptions which are radically different; for example, some costs are based upon the gross output and others on the net output to feeders, giving results which may vary from 2 to 5 per cent, and yet both may be correct.

This paper is presented with the hope that the Standards Committee may consider the time opportune to adopt a standard method of determining power costs in steam plants using coal, oil or gas for fuel, whereby the various items that enter into the cost of generating electricity can be compared, and at the same time, ascertain whether or not the plant is realizing its full efficiency.

The modern tendency to consolidation of small plants also renders it essential that not only should costs be determined, but that some method should be established whereby the costs in different plants can be corrected to allow for variation in load conditions, cost and quality of fuel, labor, etc.

The subject of this paper is naturally divided into five independent sections, as follows:

I. Production and Production Repairs Costs.
II. Investment Costs.
III. General and Miscellaneous Administration Expenses.
IV. Total Cost of Power.
V. Analysis of Production and Production Repairs Costs and Data.

For the purpose of studying the performance of individual plants, or comparing independent stations, the groups under the first four sections are arranged so that the cost of any item can be determined in cents per kilowatt-hour net output for any period. Section V gives a complete analysis of section I and of the general operating results for the same period.

I. Production and Production Repairs Costs

PRODUCTION COSTS

Group	Cost, cents per kw-hr. net output		
	Labor	Material	Total
P.A. Management and Care			
1. Superintendence			
2. Engineering Staff			
3. Chemists			
4. Clerks			
5. Messengers			
6. Janitors			
7. Watchmen			
8. Store keepers			
9. Elevatormen			
10. Miscellaneous			
Total:			
P.B. Boiler Room			
1. Engineers			
2. Water tenders			
3. Stoker operators			
4. " " assts.			
5. Firemen			
6. Firemen assts.			
7. Feed pumpmen			
8. Oilers			
9. Boiler cleaning			
10. Economizer, cleaning and oiling			
11. Ash handlers			
12. Miscellaneous			
Total:			

PRODUCTION REPAIRS COSTS

Group	Cost, cents per kw-hr. net output		
	Labor	Material	Total
R.A. Furnaces and Boilers			
1. Boilers			
2. Furnace settings (brick)			
3. Stoker and stoker engines or motors			
4. Stoker (parts inside of furnace)			
5. Grate bars			
6. Burners and atomizers			
7. Superheaters			
8. Smoke stacks			
9. Boiler insurance			
10. Miscellaneous			
Total:			
R.B. Boiler Accessories			
1. Economizers			
2. Boiler feed pumps			
3. Heaters			
4. Coal handling apparatus			
5. Ash handling apparatus			
6. Fuel oil handling apparatus			
7. Fuel gas handling apparatus			
8. Miscellaneous			
Total:			

I. Production and Production Repairs Costs—Continued

PRODUCTION COSTS	Cost, cents per kw-hr. net output		
Group	Labor	Material	Total
P.C. Engine Room			
1. Engineers			
2. Turbine operators			
3. Wipers			
4. Air pumpmen			
5. Engine oilers			
6. Pump oilers			
7. Miscellaneous			
Total:			
P.D. Electrical			
1. Supt. and operators			
2. Switchboardmen			
3. Dynamo tenders and cleaners			
4. Oil switch attendants			
5. Storage battery attendants			
6. Wiremen			
7. Electrical laboratory			
8. Lighting system			
9. Miscellaneous			
Total:			
P.E. Fuel for Steam			
1. Coal, bituminous, tons (2240 lb.) (1016 kg.)			
2. Coal, anthracite, tons (2240 lb.) (1016 kg.)			
3. Oil barrels (hectoliters) pounds (kilograms)			
4. Gas, cu. ft. (cu. meters)			
5. Dock rental			
6. Track rental			
7. Miscellaneous			
Total:			
P.F. Water for Steam			
1. Feed water			
2. Condenser water			
3. Chemicals used in purification			
4. Condensing water			
5. Tunnel rental			
6. Miscellaneous			
Total:			

PRODUCTION REPAIRS COSTS	Cost, cents per kw-hr. net output		
Group	Labor	Material	Total
R.C. Engines			
1. Reciprocating			
2. L. P. turbines			
3. H. P. turbines			
4. Exciters			
5. Miscellaneous			
Total			
R.D. Engine Accessories			
1. Condensers, barometric and jet			
2. Condensers, surface			
3. Cooling tower			
4. Auxiliary pumps			
5. Miscellaneous			
Total:			
R.E. Piping			
1. Main steam			
2. Auxiliary steam			
3. Exhaust steam			
4. Hot water			
5. Cold water			
6. Blow off			
7. Traps			
8. Oil system			
9. Air system			
10. Miscellaneous			
Total:			
R.F. Electric Generators			
1. Engine driven			
2. Turbine driven, L.P.			
3. Turbine driven, H.P.			
4. Exciters			
5. Miscellaneous			
Total:			

I. Production and Production Repair Costs—Continued

PRODUCTION COSTS	Cost, cents per kw-hr. net output		
Group	Labor	Material	Total
P.G. Lubricants			
1. All lubricants for machinery			
2. Miscellaneous			
Total:			
P.H. Production Supplies			
1. Rags			
2. Waste			
3. Packing			
4. Fire room tools			
5. Chemical laboratory supplies			
6. Lamps and fuses			
7. Miscellaneous			
Total:			
P.I. Station Expenses			
1. Stationery and printing			
2. House water			
3. Telephone			
4. Miscellaneous			
Total:			
P.J. General			
1. Vehicle service			
2. Personal injuries			
3. Other property damage			
4. Pensions			
5. Miscellaneous			
Total:			

PRODUCTION REPAIRS COSTS	Cost, cents per kw-hr. net output		
Group	Labor	Material	Total
R.G. Electrical Accessories			
1. Oil switches			
2. Switchboards			
3. Storage battery, exciter			
4. Storage battery, control			
5. Synchronous converters or motor-generators			
6. Signal system			
7. Electrical laboratory			
8. Miscellaneous			
Total:			
R.H. Tools			
1. Machine shop			
2. Repair of all tools			
3. Cranes and hoists			
4. Miscellaneous			
Total:			
R.I. Building			
1. Building			
2. Elevators			
3. Lighting			
4. Heating			
5. Ventilating			
6. Miscellaneous			
Total:			
R.J. General			
1. Vehicle service			
2. Personal injuries			
3. Other property damage			
4. Miscellaneous			
Total:			

Summary of Production and Production Repairs Costs

Production Costs	Cost, cents per kw-hr. net output			*Production Repairs Cost*	Cost, cents per kw-hr. net output		
Group	Labor	Material	Total	Group	Labor	Material	Total
P.A. Management and Care				R.A. Furnaces and Boilers			
P.B. Boiler-Room				R.B. Boiler Accessories			
P.C. Engine-Room				R.C. Engines			
P.D. Electrical				R.D. Engine Accessories			
P.E. Fuel for Steam				R.E. Piping			
P.F. Water for Steam				R.F. Electric Generators			
P.G. Lubricants				R.G. Electrical Accessories			
P.H. Production Supplies				R.H. Tools			
P.I. Station Expenses				R.I. Building			
P.J. General				R.J. General			
Total:				Total:			

	Cost, cents per kw-hr. net output Labor and material
Production	
Production Repairs	
Total	

Definitions of Production Groups

The groups are designated by letter and the general items under the groups are numbered for convenience of reference. A miscellaneous item is added to each group to include matters not specifically covered by the general items. When general labor is chargeable to a particular group but not definitely covered by any item of that group, it should be charged to the miscellaneous item.

Group P. A. Management and Care. This includes that portion of the salaries and personal expenses of the station manager or chief engineer, mechanical engineer or superintendent, electrical engineer or superintendent; that portion of the salaries of the engineering staff, chemists and store-keepers chargeable to the generating plant; also salaries of clerks, messengers, janitors, watchmen and elevatormen.

Group P. B. Boiler Room. This covers the cost of all labor in boiler room and elsewhere in the power plant having to do with making steam; including that portion of the salaries of the

assistants to the mechanical engineer or superintendent chargeable to the boiler room; also such labor as water tenders, stoker operators, assistant stoker operators, firemen, assistant firemen, feed pumpmen, oilers, boiler cleaning, economizer cleaning and oiling, ash handlers and miscellaneous.

Coal handlers or coal passers are here called assistant stoker operators or assistant firemen, depending whether the boilers are machine- or hand-fired.

In items 9 and 10 the words "cleaner" and "oiler" are not used, as this work is usually performed by different labor in the boiler room.

Group P. C. Engine Room. This covers the cost of labor on prime movers of all kinds; including that portion of the salaries of the assistants to the mechanical engineer or superintendent that is chargeable to the engine room; also such labor as engineers, turbine operators, wipers, air pumpmen, engine oilers, pump oilers and miscellaneous charges.

Group P. D. Electrical. This covers the cost of all labor in connection with the electric generating apparatus, beginning with the generators driven by the prime movers, and including the switchboard and other auxiliary apparatus up to where the electric current leaves the station; that portion of the salaries of the assistants to the electrical engineer or superintendent that is chargeable to the electric generating apparatus; also such labor as operators, switchboardmen, dynamo tenders, dynamo cleaners, oil switch attendants, storage battery attendants, wiremen and work of the electrical laboratory force chargeable to the station; lighting system and miscellaneous charges.

Group P. E. Fuel for Steam. This covers the cost of fuel used under the boilers, for generating steam whether coal, oil or gas, at the cost delivered in the bunkers or tanks; including the cost of fuel and such labor as bucket men, conveyormen, coal hoisters, coal trimmers, trolleymen, weighers and laborers. This also includes dock rental, track rental and any special expenses incurred in disposing of ashes. No portion of the cost of boiler room labor should be charged to this group.

Group P. F. Water for Steam. This covers water for boilers and condensers; tunnel rental for condensing water; also chemicals used in purification. Water for general station purposes is not to be included.

GROUP P. G. LUBRICANTS. This covers all lubricants for machinery in the generating station, but does not include oil for transformers, or oil for lanterns.

GROUP P. H. PRODUCTION SUPPLIES. This covers the cost of all supplies used in the generating plant which are consumed in the operating process, the replacement of which does not constitute a repair or renewal; the cost of repairs of operating tools; also such matters as rags, waste, packing, fire room tools, chemical laboratory supplies, lamps and fuses. Item 7, "Miscellaneous," should include gage glasses, gage washers, gaskets, steam and air hose; bolts, screws, nails, dynamo brushes, etc.

GROUP P. I. STATION EXPENSES. This covers such matters as stationery and printing; also house water and telephone service. Item 4 "Miscellaneous," includes heating, cleaning systems, fire protection system, janitors' supplies, ice water, toilet service and care of streets, yards, sidings, etc.

GROUP P. J. GENERAL. This covers such general and miscellaneous items that are chargeable to production but not includible in any particular one of the "Production Costs" groups. The vehicle service, whether automobile or horse, can be apportioned between "Production Costs" and "Production Repairs Costs."

Charge to this group all expenditures incident to injuries to persons, and property damaged when caused directly in connection with the production of electric power, as enumerated under the following heads:

(a) *Claim Department Expenses.* This includes salaries and expenses of claim agents, investigators, adjustors, and others engaged in the investigation of accidents and adjustment of claims.

(b) *Medical Expenses.* This includes salaries, fees, and expenses of surgeons and doctors; nursing, hospital attendance, medical and surgical supplies; also other hospital expenses.

(c) *Injuries to Employees.* This includes amounts paid in settlement of claims of employees for injuries arising in the course of their employment; also wages paid to disabled employees while off duty.

(d) *Other Personal Injuries and Property Damage.* This includes amounts paid in settlement of claims of persons other than employees for personal injuries sustained in connection with production of electric power; also amounts paid in settlement of claims for damage to property not owned by the accounting corporation. If the loss is of such character that it is in whole or in part indemnifiable under any contract of insurance carried by the corporation, the indemnifiable portion of the loss shall be credited to items 2 and 3 of Group "P. J."

To this group should also be charged all law expenses in connection with the defense or settlement of damage claims chargeable to the power plant, including:

1. *Salaries and Expenses of Attorneys.* A proper proportion of the salary and expenses of the general solicitor or counsel, and salaries, fees, and expenses of attorneys engaged in this work.
2. *Court Costs and Expenses.* Fees of court stenographers, expenses connected with taking depositions, and other court expenses.
3. *Law Printing.* Cost of law books, and cost of printing briefs, court records, and similar papers.

The above accident, damage and legal expenses are independent of the "General Law Expenses" which are included in Group "A. D.," under the "General and Miscellaneous Administration Expenses."

Item 4 of Group "P. J." covers all pensions paid to retired employees of the power plant, and expenses in connection therewith.

NOTE: It is important that the expenses of personal injuries, other property damages and pensions, chargeable to the power plant, should be determined independently for the power station, as they are relatively small in comparison with those of some of the other departments. If any difficulty should arise in keeping any of these accounts, they may be estimated as accurately as possible for the purpose of determining the amount chargeable to the power plant.

When any of the operating men under Groups P. B., P. C., P. D., and P. E. are used for repair work, that portion of their time should be charged to the proper groups and items of "Production Repairs."

Definitions of Production Repairs Groups

Group R. A. Furnaces and Boilers. This covers all the cost in connection with repairing boilers and furnaces. This includes boilers, furnace settings, brick work, bridge walls, arches, jambs, stokers and stoker engines or motors, stoker bars, stoker chains, tuyeres, retorts, grate bars, etc.; damper regulators, tubes, valves, oil atomizers, oil and gas burners in furnace; superheaters and smoke stacks; also boiler insurance and miscellaneous charges.

Group R. B. Boiler Accessories. This covers all fuel handling apparatus and auxiliary apparatus in the boiler room. This includes economizers, boiler feed pumps and primary and secondary heaters; all coal handling machinery such as, tower with foundations, hoisting apparatus, elevators, weighing apparatus, conveyors, crushers, belts, links, brackets, wheels, chutes and gates; all ash handling apparatus such as, cars, conveyors, winches, motors, buckets, chains, wheels, hoppers chutes and gates; also the fuel oil and fuel gas handling apparatus including storage tanks, piping, pumps, heaters filters and meters. The miscellaneous item includes blower engines or motors, injectors and pumps for chemical purification; also water meters, etc.

Group R. C. Engines. This includes all the cost of repairing prime movers, such as reciprocating engines, low-pressure turbines, high-pressure turbines and steam-driven exciters.

Group R. D. Engine Accessories. This covers the cost of repairing accessories to the prime movers, including such matters as barometric condensers, jet condensers, surface condensers, packing tubes, renewing tubes, heads and doors, cooling tower; also air, circulating, vacuum and hot well pumps.

Group R. E. Piping. This covers the cost of repairing the piping system in connection with the making of steam and delivery thereof to the prime movers; including such matters as main steam piping, auxiliary steam, exhaust steam, hot water, cold water, blow off, traps, oil system and air system. House water piping is charged to Group "R. I."

GROUP R. F. ELECTRIC GENERATORS. This includes the cost of repairing engine or turbine driven electric generators; also motor and steam driven exciters.

GROUP R. G. ELECTRICAL ACCESSORIES. This covers the cost of repairing the electrical accessories not included in Group "R. F." This includes oil switches and equipment, switchboards and equipment, such as circuit breakers, switches, instruments, bus-bars, transformers, reactive and resistance coils; also storage batteries for exciter and control with their auxiliary apparatus; synchronous converters, motor-generators, signal system and the expenses of the electrical laboratory force chargeable to "Production Repairs."

GROUP R. H. TOOLS. This covers the cost of repairing station tools and implements that have been capitalized (except fire room tools provided for under Group "P. H."). Among the principal items in this group are blacksmiths', machinists', pipe fitters' tools, pump room tools, engine tools and cutting tools; also cranes, hoists, etc.

GROUP R. I. BUILDING. This covers the cost of repairs of buildings and structures used for power station purposes (except the coal tower which is provided for under Group "R. B."). Item No. 1 "Building" includes the cost of repairs to the building proper, foundations, fixtures therein, maintaining walks, driveways, and ground connected with building. In addition to the building this group should include elevators, lighting (except lamps and fuses); also heating, ventilating, house water piping, etc.

GROUP R. J. GENERAL. This should cover such general and miscellaneous items that are chargeable to "Production Repairs" but not includible in any particular one of the "Production Repairs" groups. The vehicle service whether automobile or horse can be apportioned between "Production" and "Production Repairs."

Personal injuries and other property damage includes all the items mentioned under Group "P. J." providing they are caused directly in connection with "Production Repairs." In cases where the distribution of any of the accounts cannot be definitely determined, apportion them on the basis of one-half to "Production" and one-half to "Production Repairs."

NOTE: Men assigned to the power station such as, foreman

of engine room repairs, machinist foremen, machinists, armature repairers, masons, painters, carpenters, blacksmiths, toolmen, steam fitters, pipe coverers, crane operators, riggers, laborers, etc. are often used for repairs to parts of the system other than the power station. In this case only that portion of the expenses chargeable to the power station should be included in the proper groups and items of "Production Repairs."

II. Investment Costs

That portion of the Total Cost of Power which comes under the heading of "Investment Costs," is for convenience divided into the following groups:

Group		Cost, cents per kw-hr. net output
I. A.	Interest	
I. B.	Taxes	
I. C.	Insurance	
I. D.	Amortization Fund	
I. E.	Miscellaneous	
	Total:	

Definitions of Investment Groups

Group I. A. Interest. This covers interest on all capital invested in the power plant including land, buildings and equipment. The amount of interest chargeable to the power plant should be readjusted when necessitated by such changes as additions, betterments, withdrawals, etc.

Group I. B. Taxes. This includes all taxes in connection with and chargeable to the power plant, including land, building and equipment. State franchise tax, revenue tax, etc., should be apportioned on the same basis as the "General and Miscellaneous Administration Expenses," explained under section III. The amount of taxes charged to the power plant should also be readjusted at suitable periods.

Group I. C. Insurance. This covers all fire, casualty, and other insurance that is strictly chargeable to the total operating cost of the power plant. Boiler insurance is included in group "R. K." under "Production Repairs."

Amortization Fund.

Group I. D. In order to define clearly what is meant here by "Amortization Fund" it may be helpful to give a brief

discussion of depreciation to such extent as may be necessary to determine its general relation to the operating costs of steam-driven power plants.

Depreciation may be divided into two general classes: (1) physical depreciation, (2) functional depreciation.

Physical depreciation is the result of deterioration due to wear and tear caused by regular use, decay and the action of the elements. This class of depreciation should be taken care of by maintenance and repairs and everything charged directly to the various groups under "Production Repairs," necessary to keep the plant at 100 per cent efficiency. With this method of keeping accounts the word "depreciation" due to wear and tear, disappears.

Functional depreciation is the result of lack of adaptation to function, caused by obsolescence and inadequacy. Obsolescence is due to changes or advances in the art which renders a piece of apparatus, or a whole class of it, obsolete and uneconomical of use, as compared with new types which have been developed at a later date and which are much more efficient. It is probable that an expensive machine which is in good working order may become obsolete and require replacement well within its expectation of life.

Inadequacy results from changed conditions, growth or decline of business, rendering the apparatus or property inadequate for its purpose, and necessitating the installation of machinery capable of better meeting the requirements.

This class of depreciation cannot be prevented by maintenance, or offset by repairs, but can only be taken care of by complete replacement, and should therefore be provided for by means of a renewal, reserve fund or "Amortization Fund", the term by which it is designated in this paper. With the "Amortization Fund" an arbitrary percentage should be set aside and that percentage corrected, if necessary periodically, so that when the apparatus is condemned on account of obsolescence or inadequacy, there will be a fund which will meet the expenses.

It is a difficult matter to predict in advance the length of time that a piece of apparatus or an entire plant may remain in good serviceable condition before it becomes ineffective, and for this reason the amount originally estimated to be set aside periodically should be taken up for revision, say, every five or ten years, and an adjustment should be made by increasing or diminishing the allowance as the circumstances may require.

The amount estimated to be set aside is to be charged to operating expenses as covered by group "I. D." (Amortization Fund) under "Investment Costs," and the money so charged to be taken and invested at compound interest so that the accumulated amount will equal the original cost less scrap value at the end of the assumed life. Under the "Amortization Fund" method the existing fund is always less than it would be under the straight line method.

There are two ways in which the "Amortization Fund" can be invested: first, in securities with a regular market value and thus saleable at any time and in which case there would be a nominal rate of interest; second, this fund can be invested in the company's own business, provided it be left in such a way as will render it readily available when needed; in this case a higher rate of interest may be expected. The objection to the first scheme is that the company borrows money at a high rate of interest and loans it at a low rate of interest. However, it is not within the scope of this paper to discuss the nature of investment, but to recommend that a fund be provided to cover the expenses when it is necessary to scrap old apparatus and replace with new.

The expense of all replacements or renewals which do not have any substantial increase in capacity over the equipment or apparatus for which they were substituted, is to be covered by the "Amortization Fund." Where a substitute has a substantially greater capacity than that for which it is substituted, the cost of substitution of one of the same capacity as the apparatus replaced should be taken care of by the "Amortization Fund," and the remaining portion of the cost of the actual substitute should be charged to capital account.

To establish the amount to be set aside annually for apparatus or power plant, it will be necessary first, to determine the original cost, scrap value, estimated life and rate of interest to be received.

Cost of Apparatus or Power Plant. Where the "Amortization Fund" is started at the beginning of the plant's service, the original cost less the estimated scrap value should be used as the basis upon which to determine the rate. Where the account is not started for some years after the plant is put into operation, the value used should be the original cost less scrap value less the amount that would be existing in the invested

fund at that time if there had been an "Amortization Fund" started at the beginning of the plant's service.

Scrap Value. By scrap value is meant the fair market price of old apparatus after deducting the cost of removal. It is a difficult matter to anticipate just what the scrap value will be as with nearly all equipment, it depends upon its condition when it becomes obsolete or inadequate. If the apparatus is still serviceable a higher price than scrap value may be obtainable, and its worth in this case is characterized as "Salvage Value." For the purpose of determining the amortization fund rate, we will consider only the scrap value and assume the approximate values in percentage of the original cost as indicated in the Life Expectancy Table that follows.

Estimated Life of Apparatus. How long apparatus or equipment will remain in service before it becomes obsolete, inadequate or ineffective, is purely a speculative matter. Past experience, knowledge of the art and careful judgment are the only factors available for arriving at the probable life of apparatus and property. For this reason the Amortization Fund rate should be adjusted periodically as the life of some apparatus may be longer and some shorter than anticipated.

The following "Life Expectancy Table" we believe gives fairly representative figures of what may be expected in first-class steam-driven power plants of to-day.

TABLE I—LIFE EXPECTANCY TABLE

Property	Total life (years)	Scrap value, per cent of original cost
Buildings	75	5
Boilers, stokers and furnaces	20	5
Conveyers, elevators and hoists	20	1
Turbines, complete	12	10
Engines and condensers	12	10
Piping, values and traps	12	3
Pumps	12	5
Synchronous converters, transformers and exciters, etc.	20	10
Switching apparatus and instruments	12	5
Alternators	12	10
Motors	20	10
Tools and sundries	10	3
Storage batteries	10	10

Interest on Invested Fund. The rate of interest that will be received on the money set aside for renewals under the "Amorti-

zation Fund" will depend upon where and how the fund is invested.

The following illustration will demonstrate how the amount to be set aside annually at compound interest for the "Amortization Fund" can be determined for a new Steam-Driven Turbine Power Plant costing $75 per kilowatt economical rating including the building and equipment complete. Land generally appreciates and therefore is not considered in this illustration.

The first operation will be to ascertain the original cost of each principal item as given in the "Life Expectancy Table", the sum of which must be equal to the total original cost of the plant, and then deduct the scrap value to obtain the cost on which to base the "Amortization Fund." The annual amount to be charged to the "Amortization Fund" for each item and to be set aside at 4 per cent compound interest which will accumulate a sum equal to the original cost less the scrap value at the end of the expected life, can be computed from standard annuity tables.

The costs per kilowatt economical rating of the various elements entering into the power plant as given in Table II, are only approximate for steam turbine plants having a capacity of 25,000 kw. or more.

TABLE II

Property	Original cost per kilowatt economic rating	Total original cost of 25,000-kilowatt plant	Total original cost less scrap value of 25,000-kilowatt plant	Annual charge to "Amortization Fund"
Building	$20.00	$500,000	$475,000	$1,059
Boilers, stokers and furnaces	21.00	525,000	498,750	16,750
Conveyors, elevators and hoists	4.50	112,500	111,375	3,741
Turbines, complete	10.00	250,000	225,000	14,970
Condensers	4.25	106,250	95,625	6,408
Piping, valves and traps	4.50	112,500	109,125	7,265
Pumps	0.75	18,750	17,813	1,186
Synchronous converters, transformers, exciters, etc.	3.00	75,000	67,500	2,268
Switchboard apparatus and instruments	3.80	95,000	90,250	6,006
Motors	0.20	5,000	4,500	151
Tools and sundries	3.00	75,000	72,125	5,938
	$75.00	$1,875,000	$1,748,188	$65,742

It will be seen from Table II that when the scrap value is deducted $1,748,188 or 93.2 per cent of the original cost of the plant including building and complete equipment, remains to be covered by the "Amortization Fund;" 27.2 per cent of the $1,748,188 represents the building and 72.8 per cent the equipment.

The amount to be set aside annually is, $1,059 for the building and $64,683 for the equipment or $65,742 for the entire plant, which is equivalent to 0.223 per cent of the total original cost of the building less scrap value and 5.08 per cent of the total original cost of the equipment less scrap value or 3.76 per cent of the total original cost of building and equipment less scrap values respectively.

In case an "Amortization Fund" has not been maintained at all for a large part of the plants' life and it is desired to provide for a portion of the equipment and building during the remaining life, the operation will be the same as described above with the exception that it will be necessary to determine the value as stated under the heading "Cost of Apparatus or Power Plant," and estimate the remaining life.

The average weighted life of the equipment complete, considered as a whole, is obtained by multiplying the assumed life in years of each item by the cost of the item and dividing the sum by the total cost of all the equipment. The average weighted life in this illustration is approximately 16 years.

Readjustment of Amortization Fund. The percentage or amount that is annually set aside for the "Amortization Fund" should be periodically readjusted to correct for the possible change in assumed life, increase or decrease in cost due to additions, replacements or renewals and withdrawals.

If after a plant has been in operation for five years it is found that the estimated life of certain portions of the equipment is longer and other portions shorter than was anticipated, the "Amortization Fund" can be readjusted as follows:

Establish a new "Life Expectancy Table" and obtain the remaining life of each item upon which the revised annual charge is to be based. Determine the cost of each item for calculating the revised percentage to be set aside, by deducting from the "Total Original Cost Less Scrap Value" given in Table II, the amount of the "Amortization Fund" at the end of 5 years plus the compound interest on this amount at 4 per cent for a period equal to the remaining life. The

"Revised Annual Charge to the Amortization Fund" can be then computed from annuity tables as in the previous illustration.

TABLE III—LIFE EXPECTANCY TABLE

Property	Estimated total life in years		Revised remaining life after 5 years
	Original	Revised	
Building	75	75	70
Boilers, stokers and furnaces	20	18	13
Conveyors, elevators and hoists	20	15	10
Turbines, complete	12	10	5
Condensers	12	10	5
Piping, valves and traps	12	10	5
Pumps	12	10	5
Synchronous converters, transformers, exciters, etc.	20	22	17
Switchboard apparatus and instruments	12	14	9
Motors	20	15	10
Tools and sundries	10	12	7

The average weighted life of the equipment taken as a whole on the basis of the revised "Life Expectancy Table" is 14.5 years, whereas with the originally estimated life it is 16 years.

TABLE IV

Property	Total original cost less scrap value of 25,000 kilowatt plant	Original cost less scrap value, A. P. amount for 5 years, and interest of amount for remaining life	Revised annual charge to Amortization Fund
Building	$475,000	$385,663	$1,059
Boilers, stokers and furnaces	408,750	347,750	20,915
Conveyors, elevators and hoists	111,375	81,385	6,782
Turbines, complete	225,000	126,340	23,320
Condensers	95,625	53,410	9,870
Piping, valves and traps	109,125	61,275	11,320
Pumps	17,813	10,002	1,847
Synchronous converters, transformers, Exciters, etc.	67,500	43,580	1,839
Switchboard apparatus and instrument	90,250	43,930	4,150
Motors	4,500	3,289	274
Tools and sundries	71,250	28,910	3,660
	$1,748,188	$1,185,534	$85,035

From the above table it will be seen that the amount to be set aside annually is $1,059 for the building and $83,977 for the equipment or $85,036 for the entire plant. The percentage that is to be set aside after 5 years is 4.86 per cent of the total original cost of the building and equipment less scrap value, which is an increase of approximately 29.5 per cent over that originally estimated.

In a similar way the "Amortization Fund" should be readjusted when additional equipment is installed, old apparatus renewed, replaced or withdrawn.

GROUP I. E. MISCELLANEOUS. Charge to this group that portion of other investment costs chargeable to the "Total Cost of Power" and not specifically covered by any of the above groups.

Annual expenses of franchises and other intangible capital not specifically a departmental charge is to be apportioned as explained in Section III, "General and Miscellaneous Administration Expenses."

III. GENERAL AND MISCELLANEOUS ADMINISTRATION EXPENSES.

The "General and Miscellaneous Administration Expenses" are chargeable to all departments and to make an equitable distribution of these expenses it is proposed to deduct the charges that are clearly departmental charges, such as, boiler insurance, casualty insurance, other insurance, personal injuries, damage to other property, pensions etc., and to apportion the remainder on the basis of the percentage of the departmental costs (exclusive of the General and Miscellaneous Administration Expenses and Investment Costs) to the total "Running Expenses" of the corporation.

For illustration, the portion of "General and Miscellaneous Administration Expenses" chargeable to the power plant in percentage, is,

$$\frac{\text{Total production costs plus total production repairs costs}}{\text{Total running expenses of the corporation}} \times 100$$

After this percentage is determined, the amounts chargeable to the power plant and covered by the groups under "General and Miscellaneous Administration Expenses," can be obtained and the cost per kw-hr. net output calculated.

GENERAL AND MISCELLANEOUS ADMINISTRATION EXPENSES.

Group	Cost, cents per kw-hr. net output
A. A. Salaries and Expenses of General Officers	
A. B. Salaries and Expenses of General Office Clerks	
A. C. General Office Supplies and Expenses	
A. D. General Law Expense	
A. E. Relief Department	
A. F. General Stationery and Printing	
A. G. Store Expenses	
A. H. Miscellaneous General Expenses	
Total:	

Definitions of General and Miscellaneous Administration Groups

GROUP A. A. SALARIES AND EXPENSES OF GENERAL OFFICERS. This includes the salaries, traveling and incidental expenses of the directors, president, vice-president, treasurer, secretary, comptroller, general auditor, general manager, assistant general manager, chief engineer, general superintendent, purchasing agent, and all other officers whose jurisdiction extends to the entire system and whose services cannot be satisfactorily allocated to the several departments.

GROUP A. B. SALARIES AND EXPENSES OF GENERAL OFFICE CLERKS. This includes the salaries and traveling and incidental expenses of general office auditors, bookkeepers, cashiers, paymasters, stenographers, clerks employed in counting cash, and all other clerks employed in the general office.

Salaries and expenses of clerks in the commercial department are not to be charged to this group.

GROUP A. C. GENERAL OFFICE SUPPLIES AND EXPENSES. This covers the cost of office supplies, repairs of office furniture, and renewals of such furniture as has not been capitalized; wages of janitors, porters, and messengers; rent of rooms in office buildings, repairs of such rented rooms, and all other miscellaneous expenses of general offices. Office expenses of departmental officers must be charged to the proper departmental accounts.

GROUP A. D. GENERAL LAW EXPENSES. This covers all law expenses except those incurred in the defense and settlement of damage claims, chargeable to the power plant and

covered by Groups "P. J." and "R. T." and those chargeable to other departments. This includes salaries and expenses of all counsel, solicitors and attorneys, their clerks and attendants, and expenses of their offices; cost of law books, printing briefs, legal forms, testimony, reports, etc.; fees and retainers for services of attorneys not regular employees; court costs and payments of special, notarial and witness fees not provided for elsewhere; expenses connected with taking depositions and all law and court expenses not provided for elsewhere.

GROUP A. E. RELIEF DEPARTMENT. This covers all salaries and expenses incurred in connection with conducting a relief department; also contributions made to such department.

NOTE. All pensions paid to retired employees, and expenses in connection therewith are charged directly to the department and in case of the power plant, it is covered by item 4 under Group "P. J." of "Production Costs."

GROUP A. F. GENERAL STATIONERY AND PRINTING. This includes all expenses for stationery and printing, stationery supplies and postage except as hereinafter provided:

The cost of printing briefs and other legal papers shall be charged to Group "A. D.," "General Law Expenses," or Groups "P. J." and "R. T." in accordance with the purpose of the printing.

The cost of printing signs, posters, and other advertising matter shall not be charged to this group, as no portion of such expenses are chargeable to the power plant.

The cost of such mechanical calculators, typewriters, duplicating machines and other office appliances as are not properly capitalized, shall, if for use in general offices, be charged to Group "A. C.," "General Office Supplies and Expenses." If these appliances are for use of departmental offices, they should not be charged to this group, but to departmental accounts.

GROUP A. G. STORE EXPENSES. Charge to this group all salaries and expenses in connection with store-rooms, including cost of sending material and supplies from general store-rooms to branch store-rooms, and the collection of scrap material.

GROUP A. H. MISCELLANEOUS GENERAL EXPENSES. This covers the cost of telephone service, telegrams, and all other miscellaneous expenses not specifically covered by any one of the "General and Miscellaneous Administration Expenses" groups.

IV. Total Cost of Power

The total cost of power as covered by this section is conveniently divided into two distinct parts and includes all the costs chargeable to the power plant and that have to do with the production of power, but does not include any portion of the transmission, distribution, utilization or commercial expenses. First, for comparative purposes and for a study of plant economics the total cost of power should consist of production costs plus production repairs costs plus investment costs. Second, for the purpose of exchanging or selling power or for a study of independent plants with a view of combination, the total cost of power should include production costs plus production repairs costs plus investment costs plus General and Miscellaneous Administration Expenses.

Sections	Costs, cents per kw-hr. net output
I. Production Cost.....	
I. Production Repairs Cost.....	
II. Investment Cost.....	
Total Cost of Sections I and II.	
III. General and Miscellaneous Administration Expenses.....	
Total Cost of Sections I, II, and III	

V. Analysis of Production and Production Repairs Costs and Data

Item

1. Cost of Production plus Production Repairs in cents per kw-hr. net output...
2. Percentage of fuel cost to the cost of Production plus Production Repairs...
3. Percentage of labor cost of Production and Production Repairs to total cost of Production and Production Repairs.....
4. Percentage of fuel cost to labor cost of Production and Production Repairs..
5. Percentage of cost of Production and Production Repairs used for repair materials, supplies etc. (100—items 2 and 3).....
6. Percentage of total Production cost to total cost of Production and Production Repairs.....
7. Percentage of total cost of Production Repairs to total cost of Production and Production Repairs.....
8. Percentage of total cost of Production Repairs to total cost of Production...
9. Average daily wages per man.....
10. Kilowatt hours net output per man.....
11. Cost of feed water per 1000 cubic feet (28.32 cubic meters).....
12. Boiler feed water purchased per kw-hr. net output, pounds (kilograms).....
13. Cost of handling coal per ton (2240 lb.) (1016 kg.).....

14. Average cost { Coal per ton (2240 lb.) (1016 kg.)
Fuel oil per barrel (42 U. S. gallons (1.59 hectoliters)....
Fuel gas per 1000 cubic feet (28.32 cu. meters)

15. Average B.t.u. (large calories) { Coal per lb. (0.4534 kg.) (moist, as received)
Fuel oil per pound (0.4534 kg.).....
Fuel gas per cubic foot (0.028 cu. meter)

16. Average B.t.u. (large calories) per dollar { Coal
Fuel oil.....
Fuel gas.

17. B.t.u. (large calories) supplied per kw-hr. net output { Coal
Fuel oil.....
Fuel gas

18. Coal factor = coal per kw-hr. net output (pounds) (kilograms).....

19. Fuel oil per kw-hr. net output (pounds) (kilograms).....

20. Fuel gas per kw-hr. net output (cubic feet) (cu. meters).....

21. Kw-hr. net output { Coal per ton (2240 lb.) (1016 kg.)
Fuel oil per barrel (42 U. S. gallons) (1.59 hectoliters)
Fuel gas per (1000 cu. ft.) (28.32 cu. meters)

22. Kind and size of coal.....

23. Kind of fuel oil and sp. gr.....

24. Kind of fuel gas.....

25. Average percentage of ash in coal as received.....

26. Average B.t.u. (large calories) per pound (0.4534 kg.) of refuse from coal....

27. Net thermal efficiency of plant in per cent

$$= \frac{\text{Total kilowatt hours net output} \times 3415}{\text{Average B.t.u. per ton} \times \text{tons of coal used}} \times 100$$

28. Load factor of load.....

29. Figure of merit (for coal)

$$= \frac{\text{B.t.u. per ton (Moist)} - \left(\frac{2240 \times \%\ \text{ash}}{100} \times \text{B.t.u. per pound of refuse}\right)}{\text{Price per ton (2240 lb.) (\$)}}$$

$$= \frac{\text{Large calories per 1016 kg.} - \left(\frac{1016\ \text{kg.} \times \%\ \text{ash}}{100} \times \text{large calories per kg. of refuse}\right)}{\text{Price per 1016 kg. (\$)}}$$

Discussion of Analysis of Production and Production Repairs Costs and Data

ITEM 1. This figure is determined by dividing the total Production and Production Repairs costs by the total kilowatt-hours net output for the period. By net output is meant the power that leaves the generating station for distribution. The total cost of Production and Production Repairs per kilowatt-hour as obtained from summary under Section I, will give the same result.

ITEM 2. This figure is obtained by dividing the total cost of fuel by the total cost of Production and Production Repairs

and multiplying by 100, or by dividing the cost of material only in Group "P. E.," by the cost of Production plus Production Repairs per kilowatt-hour as obtained from the summary under Section I and multiplying by 100.

ITEM 3. Divide the total cost of labor of Production and Production Repairs by the total cost of Production and Production Repairs and multiply by 100, or divide the cost of labor per kilowatt-hour in all the groups by the total cost per kilowatt-hour given in the summary of Section I and multiply by 100.

ITEM 4. Divide the total cost of fuel by the total cost of labor of Production and Production Repairs and multiply by 100, or divide the cost of material only, in Group "P. E.," by the total cost of labor per kilowatt-hour in all the groups as obtained from summary of Section I, and multiply by 100.

ITEM 5. Determine this figure by subtracting the percentages obtained in Items 2 and 3 from 100.

ITEM 6. Divide the total cost of Production by the total cost of Production and Production Repairs and multiply by 100, or divide the total cost of Production per kilowatt-hour by the total cost of Production and Production Repairs per kilowatt-hour and multiply by 100.

ITEM 7. Obtain this figure by dividing the total cost of Production Repairs by the total cost of Production and Production Repairs and multiplying by 100, or divide the total cost of Production Repairs per kilowatt-hour by the total cost of Production and Production Repairs per kilowatt-hour and multiply by 100.

ITEM. 8. Divide the total cost of Production Repairs by the total cost of Production and multiply by 100, or divide the total cost of Production Repairs per kilowatt-hour by the total cost of Production per kilowatt-hour and multiply by 100.

ITEM 9. Obtain this figure by dividing the total daily cost of all labor by the total number of men included in all the "Production" and "Production Repair" groups with the exception of Group "P. A." The "Average Daily Wages per Man" is materially affected by local conditions and this should be taken into consideration when comparing power costs. The "Reduction Factor" to be used in this case is the ratio of the lower to the higher "Average Daily Wages per Man."

To compare the cost per kilowatt-hour net output of two independent plants on the same basis, apply the "Reduction Factor" to labor only of all groups with the exception of Group "P. A." and add or subtract the difference to or from the total cost of "Production" plus "Production Repairs" per kilowatt-hour net output.

Group "P. A." "Management and Care," is practically independent of load conditions and labor unions and is therefore not considered in applying the "Reduction Factor" for labor.

ITEM 10. This figure is obtained on the basis of all men included in the Production and Production Repairs groups with the exception of Group "P. A." The kilowatt-hours per man increase as the station becomes larger in size, and consequently the cost of labor per unit generated becomes less.

ITEM 11. This figure is determined by dividing the total cost of feed water delivered by the number of 1000 cubic feet (28.32 cu. meters) received. If there is any additional pumping charge, it should be included in the cost of water.

ITEM 12. This figure can be determined by dividing the water purchased by meter for the boilers by the total kilowatt-hours net output.

ITEM 13. Divide the total cost of labor as covered by Group "P. E." items 1 and 2 by the total number of tons of coal handled. The cost of labor for coal handling apparatus in Group "R. B" item 4 is not to be included.

ITEM 14. These figures are to be determined on the basis of what was actually paid for the fuel.

ITEM 15. The calorific values of coal and fuel oil should be determined by the bomb type calorimeter in which the combustible is burned in the presence of oxygen under pressure, as this is the most accurate and satisfactory device for solid fuels. The gaseous fuels should be tested in a recognized standard calorimeter equivalent to the Junker.

ITEM 16. Determine these figures by dividing the total B.t.u. (large calories) in fuel as received, by the actual cost of the fuel.

ITEM 17. Determine these figures by dividing the total B.t.u. (large calories) contained in the fuel, by the total kilowatt-hours net output for the period. The total B.t.u. (large calories) contained in the fuel is equal to the B.t.u. (large calories) obtained

from proximate analysis, multiplied by the total number of pounds (0.4534 kg.) of coal, oil or cubic feet (0.028 cu. meter) of gas used.

ITEM 18. Divide the total number of pounds (kilograms) of coal used by the total kilowatt-hours net output.

ITEM 19. Divide the total number of pounds (kilograms) of fuel oil used by the total kilowatt-hours net output.

ITEM 20. Divide the total number of cubic feet (cu. meters) of gas used by the total kilowatt-hours net output.

ITEM 21. These figures can be obtained by dividing the total kilowatt-hours net output by the total amount of fuel used. One barrel equals 42 U. S. gallons or 1.59 hectoliters.

ITEM 22. State whether, anthracite, semi-anthracite, bituminous, semi-bitumious also if pea, No. 1, No. 2 or No. 3 buckwheat or rice coal, etc.

ITEM 23. State if crude or distilled or reduced fuel oil. The average heating value per pound of crude oil generally increases as the specific gravity diminishes, but the specific gravity of an oil is not an accurate index of its calorific value. However, it may be of interest for comparison to give the specific gravity under this item.

ITEM 24. State whether natural gas, coal gas or producer-gas, etc.

ITEM 25. This is determined by the usual proximate analysis which is made when the coal is received.

ITEM 26. This is determined by making a series of tests during the period on the refuse taken from the ash heap, sampled and analyzed in the same manner as the coal in Item 15.

ITEM 27. The net thermal efficiency of a steam-driven power plant in per cent is

$$\frac{\text{Total kilowatt-hours net output} \times 3415}{\text{Average B.t.u. per ton} \times \text{tons of coal used}} \times 100$$

Average B.t.u. per ton (moist, as received) is obtained by multiplying item 15 by 2240.

The net thermal efficiency is the true measure of the scientific perfection of the design of plant, whereas the cost per kilowatt-hour is the true engineering criterion of the perfection in efficiency of the plant.

Relation Between Load Factor and Costs

ITEM 28. The term "load factor" has been used in so many different ways, that much confusion still exists among a number of central station men. In some instances maximum station capacity, machine rating and connected load when considering a motor load are used, instead of actual maximum load. Load factor based upon the rated capacity shows a wide amount of variation, but when based upon the actual maximum load upon the plant during the period, it is considerably more uniform. If load factor figures are to be of any value for comparative purposes, they must be on a uniform basis, using the total number of hours in the period under consideration.

Load factor, as used in this case, is load factor of the load for any period and is defined as the ratio of actual net output during the period, to the net maximum hour's load multiplied by the total hours in the period. Thus daily load factor of load in per cent $= \frac{\text{Actual net output for day of 24 hours}}{\text{Net maximum hour's load} \times 24} \times 100$. For the purpose of comparing any two plants for a given period the load factor of the load on the basis of the maximum hour during the period should be used and not the average of daily load factors. The monthly load factor of load is usually much lower than the average of daily load factors. In railway service the peaks on Saturdays, Sundays and holidays are comparatively small and consequently the load factor is relatively higher than on other days. In lighting stations the load factor is usually higher on Saturdays and holidays and lower on Sundays than on other days.

Load factor has an important effect on the cost of producing power. A low load factor involves the use of relatively large equipment operating at light and inefficient loads, but with a high load factor, all the elements that enter into the production of power are operating at maximum economy, and the cost of power is at a minimum. In any given system using coal as fuel, with approximately the same average maximum hour load the following relative changes take place with a change in load factor, providing the load factor remains changed over a reasonably long period of say at least six months.

The total cost of management and care is practically constant and independent of the load factor, but the cost per kilowatt-

hour net output increases as the load factor decreases. To a certain extent the cost of labor varies with the load factor, but at about 25 per cent load factor the number of men required to operate the plant seems to reach a minimum, and below this point, it practically remains constant. The total cost of water, lubricants, supplies and most of the repairs, varies almost directly with the load factor, as the costs of these individual items are practically functions of machine hours. The total cost of coal varies with the load factor but not quite so rapidly, whereas the cost of coal per kilowatt-hour net output increases with a decreasing load factor. The total kilowatt-hour net output, turbine, engine and active fire hours vary directly with the load factor. The banked fire hours increase with a decrease in load factor but not quite so rapidly. The reserve fire hours slightly increase with a decrease in load factor.

It has been found that the relationship between load factor and cost of production plus production repairs in a first-class steam plant using coal as fuel, is that the cost per kilowatt-hour net output varies approximately as the inverse fourth root of the load factor. This law will hold between 15 per cent and 90 per cent load factors and is applicable to individual plants, but in comparing independent plants the cost of power in each plant should be reduced to a common load factor.

Fig. 1 illustrates graphically the relation between the cost of power and load factor for steam turbine plants of 25,000 kilowatts capacity and larger, using coal costing $3.00 per ton, having 14,500 B.t.u. per pound or approximately 10,840,000 B.t.u. per dollar. The investment costs are shown by the curves above and the cost of producing power by the curves below the axis, so that the sum of the ordinates gives the total cost per kilowatt-hour net output for any load factor.

The full line curves are for a steam turbine plant operating at normal rating which is here considered to be the economical rating of the prime mover. The cost of equipment and building is taken at $75 and the land at $6 per kilowatt economical rating. The dotted lines show the charges for a plant operating at the maximum two-hour overload rating of the prime mover. In this case the cost of equipment and building is reduced to $60 and the land to $4.8 per kilowatt maximum two-hour overload rating. In each case 5 per cent is allowed for interest, 1 per cent for taxes, 1 per cent for insurance and 3.5 per cent for amortization fund, making a total investment charge of 10.5 per cent.

It is readily seen from the curves that the most important item entering into the cost of production and production repairs is that of fuel, and during the greater part of the day when the load is relatively light the investment costs unquestionably have

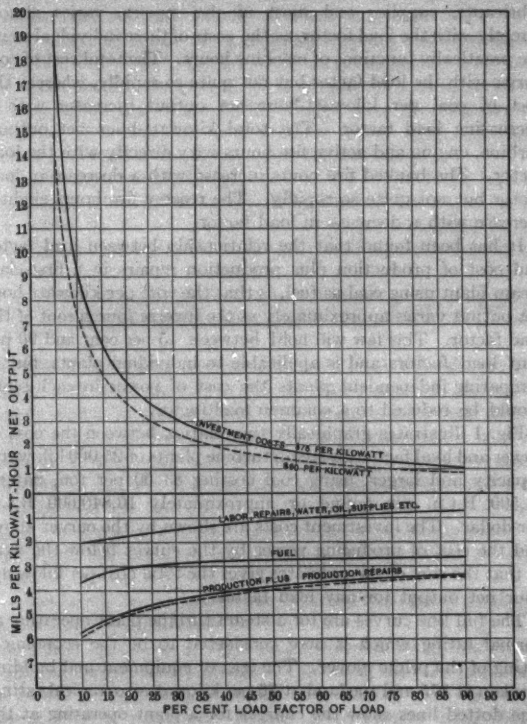


FIG. 1

the greatest influence on the total cost of power. At 20 per cent load factor the investment costs are approximately equal to the production plus production repairs costs for the $75 plant, and become much higher as the load factor decreases. The total

yearly investment costs is dependent upon the rated capacity but independent of the output.

The lower dotted curve shows the cost of production plus production repairs during the maximum hour periods when operating at maximum overload rating or 25 per cent above economical rating. This is approximately 2.25 per cent higher than the cost for economic operation. During the other periods the cost will be the same as when operating at normal rating or maximum economy.

If at any load factor the two ordinates are added it will be found that the total cost of power is less when operating at overload rating notwithstanding the increase in cost due to poor economy at overload. This shows the marked influence of the investment costs on the total cost of power. In other words with sufficient margin for insurance the plant can be run at the maximum overload capacity during the maximum hour periods at the sacrifice of a large percentage in efficiency during these periods.

The investment cost curve is obtained by dividing a constant by a variable and consequently it is an equilateral hyperbola. The equation of this curve referred to its asymptotes as co-ordinates which are at right angles is

$$Y_1 = \frac{x\, y_i}{X} \tag{1}$$

in which Y_1 represents the investment cost in mills per kilowatt-hour net output, X the corresponding load factor of load expressed in per cent and $x\, y_i$ a constant for any given curve, where x and y_i are the co-ordinates of any point on the curve. To compute the investment costs of any plant for any load factor it will be necessary first to determine the value of $x\, y_i$ in which x represents the present load factor and y_i the corresponding investment cost.

The curve showing the cost of production plus production repairs per kilowatt net output is an inverse fourth root curve and is represented by the equation

$$Y_p = \frac{y_p \sqrt[4]{x}}{\sqrt[4]{X}} \tag{2}$$

in which Y_p represents the cost in mills per kilowatt-hour net output, X the corresponding load factor of load in per cent and $y_p \sqrt[4]{x}$ a constant for any given curve, where x and y_p

are the co-ordinates of any point on the curve. To compute the production plus the production costs of any station for any load factor, first determine the value of $y_p \sqrt[4]{x}$, where x is the present load factor and y_p the corresponding cost.

Illustration: If a plant is operating at 30 per cent load factor with a cost of 4.4 mills for production plus production repairs and 3.1 mills for investment, making a total cost of 7.5 mills per kilowatt net output, what will be the cost if the plant were operated at 50 per cent load factor?

Investment Cost

$$Y_I = \frac{30 \times 3.1}{50} = 1.86 \text{ mills}$$

Production plus Production Repairs Costs

$$Y_P = \frac{4.4 \sqrt[4]{30}}{\sqrt[4]{50}} = 3.87 \text{ mills}$$

Total cost of power per kilowatt net output.....5.73 mills

If it is desired to obtain the total cost of power including the "General and Miscellaneous Administration Expenses," it will be necessary to determine the cost in mills per kilowatt net output of Groups "A.A." to "A.H." as discussed under section III when operating at 30 per cent load factor, substitute in equation (1), solve for Y and add the result to the above figures 5.73 mills.

Figure of Merit and Reduction Factor for Determining Relative Value of Coals

Item 29. The item of fuel has such an important influence on the cost of producing power, that in order to compare the economy of operation of different plants it is necessary to know the character and cost of coal used in each case. In order to establish an equitable basis upon which one coal can be compared with another of different price and from a different locality, the term "Figure of Merit" is proposed, which represents the B.t.u. per dollar after correcting for ash, and B.t.u. lost in refuse as follows:

Figure of merit

$$= \frac{\text{B.t.u. per ton (moist)} - \left(\frac{2240 \times \%\text{ ash}}{100} \times \text{B.t.u. per pound of refuse}\right)}{\text{Price per ton, (2240 lb.) (\$)}}$$

The B.t.u. per ton (moist, as received), is obtained by multiplying item No. 15 by 2240. Percentage of ash in coal as received and the B.t.u. in refuse from the coal are obtained from items 25 and 26. The price per ton of coal (2240 lb.) is the actual price paid the contractor. For illustration take two coals, "A" and "B":

Coal	B.t.u. per pound moist	Price per ton (2240 lb.)	Percentage of ash in coal as received	B.t.u. per pound refuse	Figure of merit
A	14,500	$3.00	5	3,500	10,696,000
B	13,000	2.00	10	4,000	14,112,000

The "Figure of Merit" of coal "B" is approximately 32 per cent higher than that of coal "A."

For the purpose of comparing the production costs per kilowatt-hour on a common basis, using fuel having the same "Figure of Merit," it will be necessary to adopt a "Reduction Factor" for correcting the cost of coal having the lowest "Figure of Merit," "Reduction Factor," being defined as the ratio of the lower to the higher "Figure of Merit." In the above illustration the "Reduction Factor" is

$$\frac{\text{Figure of merit coal "A"}}{\text{Figure of merit coal "B"}} = \frac{10{,}696{,}000}{14{,}112{,}000} = 0.758$$

Applying this factor to coal "A" is equivalent to saying that in order to compare coals "A" and "B" on the same basis, with respect to B.t.u., percentage of ash in the coal, B.t.u. in the refuse and the price per ton, coal "A" should cost $2.27 per ton instead of $3.00. If it is desired to compare the costs per kilowatt-hour net output on the same basis, one using coal "A" and the other coal "B," apply the "Reduction Factor" to cost of fuel (material only) in group "P. E." items 1 and 2 of plant using coal "A" and subtract the difference from the total cost of "Production" per kw-hr. net output.

Application of Factors

In comparing the power costs of two independent plants, the "Average Daily Wages per Man" "Figure of Merit of Coal" and "Load Factor of Load" must always be taken into consideration, and the plant having the lowest cost per kilowatt-hour

net output should be the proper standard for comparison. If it is desired to compare plants "A" and "B" when the former has the lower power cost, the corrected cost of plant "B" can be computed from the following formula:

$$Y = \frac{x\,y_i}{X} + \left[y_p - L\,(1 - F_L^{\pm 1}) - C\,(1 - F_c^{\pm 1}) \right] \frac{\sqrt[4]{x}}{\sqrt[4]{X}} \quad . . (3)$$

Y represents the corrected cost in mills per kilowatt-hour net output of investment plus production plus production repairs of plant "B."

y_i and y_p represent the original cost in mills per kilowatt-hour net output of investment and production plus production repairs respectively of plant "B."

X and x are the "Load Factors of Load" of plants "A" and "B" respectively.

L is the cost in mills per kilowatt-hour net output of all labor in all production and production repair groups with the exception of Group "P. A."

F_L is the "Reduction Factor" for labor as explained under item 9 of "Discussion of Analysis of Production and Production Repairs Cost and Data."

C represents the cost in mills per kilowatt-hour net output of coal (material only) in Group "P. E.," items 1 and 2.

F_c is the "Reduction Factor" for coal, as explained under item 29 of "Discussion of Analysis of Production and Production Repairs Cost and Data."

Use the reciprocals of F_L and F_c if the "Average Daily Wages per Man" is lower and the "Figure of Merit" is higher in plant "B" than in "A".

For illustration we will assume the following approximate figures and compute the cost of plant "B" on the basis of "A:"

Plant	Load factor	Figure of Merit	Average daily wages per man	y_i	y_p	$y_i + y_p$	L	C
A	50	14,000,000	$2.5	2.0	4.0	6.0	—	—
B	40	10,500,000	$2.0	2.5	4.5	7.0	0.13	3.0

$$F_L \text{ "Reduction Factor" for labor } = \frac{2.0}{2.5} = 0.80$$

$$F_c \text{ "Reduction Factor" for coal } = \frac{10{,}500{,}000}{14{,}000{,}000} = 0.75$$

$$Y = \frac{40 \times 2.5}{50} + \left[4.5 - 0.13\left(1 - \frac{1}{0.80}\right) - 3.0\,(1 - 0.75)\right]\frac{\sqrt{40}}{\sqrt{50}} = 5.57 \text{ mills}$$

That is, if plant "B" were operated on the same basis as plant "A" with regard to "Load Factor," "Figure of Merit" and "Average Daily Wages per Man," the cost of power per kilowatt-hour net output, including investment, production and production repairs, would be 5.57 mills, which is approximately 7.2 per cent lower than the cost for plant "A."

Summary

First. Standardization of method for determining the cost of all items that enter into the total cost of power, which is divided into three distinct sections.

Second. Method of analyzing the production and production costs and operating data for comparative purposes.

Third. Determining the relation between load factor and cost of power, so as to permit the comparison of costs per kilowatt-hour under varying conditions.

Fourth. Establishing an equitable basis for comparing the relative values of coals where the chemical analysis and price are different.

Fifth. Method of correcting for the cost of labor where the "Average Daily Wages per Man" is materially different.

In conclusion, the authors hope that this paper may be the means of arousing sufficient interest in this complex subject to insure a full and free discussion of the problems presented and that some standard method of determining power costs may result therefrom.

DISCUSSION ON "STANDARDIZATION OF METHOD FOR DETERMINING AND COMPARING POWER COSTS IN STEAM PLANTS". (STOTT AND GORSUCH), COOPERSTOWN, NEW YORK, JUNE 26, 1913.

Henry Floy: Turning to the last pages of the paper, it is a disappointment to find that the final formula, given on page 1650, in which one looks to find the solution of the problem discussed, omits a part of the "total cost" elements mentioned on page 1639. In fact the question may be fairly raised whether "General and Miscellaneous Administration Expenses" of one plant are capable of direct comparison with those of another plant upon the basis merely of output. These expenses really have little to do with the question of scientific perfection of design or efficiency of operation of a power plant. Proportioning such expenses to power costs in the relation of such costs to total costs, as mentioned on page 1636, may be unfair. This may be seen by considering the disproportionately large amount of the president's salary, for example, compared to his time or effort, that would be allotted to power cost, when based on the ratio of expense for fuel to the total expense. Perhaps a more equitable method of proportioning the general officers' salaries would be on the basis of letters found in office files relating to the different departments, or dividing auditing expenses in proportion to the vouchers passed for the various departments. Another omission from the formula presented is the failure to take into consideration for comparison, the substituted cost of water and its treatment for boiler and condensing purposes, which might be quite different, with appreciable effect on power costs, in the plants being compared.

Presumably the division of production and repair costs proposed, are along the lines of accounting established by the Public Service Commission of New York State, but pensions included in general expenses at foot of page 1622, are not in accordance with such classification. Neither is the item of interest included, as given among investments costs on page 1629. If variation from accepted rules of accounting is to be made, improvement in details should be expected. Why boiler insurance, for example, should be included as a part of repair costs and employees' insurance, with the attendant expenses, should be put in production costs, is not clear and is one of the apparent inconsistencies. It will be noted that in the substitution of one piece of apparatus for another, the authors make capacity alone the basis of capitalization charge, improved efficiency being entirely ignored. Depreciation is apparently taken to include only obsolescence and inadequacy, while extraordinary accident and "calamity", such as the floods which lately visited many plants in the central west, items which must be taken care of by reserves rather than insurance, are omitted.

The figures given in Table I, Life Expectancy, are stated to

be, what the authors believe, "fairly representative." It would be interesting to know upon what basis such statement is made, as the figures are not in accordance with those widely used and authoritative figures given, for example, in the speaker's paper on "Depreciation", presented before this Institute two years ago. It would seem only fair to criticize the use of figures which do not agree with those more or less well established and authoritative, unless the authors offer some explanation as to why their figures differ and reasons for their acceptance. The introduction of such random data, which is too common among writers of papers before this and other societies, results only in confusion and lack of uniformity, for which the profession is justly criticized. By way of further illustration, all buildings will not have the same life expectancy and the authors should differentiate between the character of buildings referred to; for example, wood, brick, steel or monolithic concrete, the lives of which will be quite different. The same with regard to scrap value. On what do the authors base their value of 5 per cent? Certainly it does not relate to wooden buildings, nor to concrete buildings, unless in exceptional cases, and the speaker has found 8 per cent is about the correct figure for the scrap value of brick and steel structures.

A similar line of criticism might be made of many of the other items mentioned in the table, the lives of which are unduly short, or of which the parts may be renewed almost indefinitely. The publication of such figures by men of such standing as the authors, leads to their use in misleading and unfair ways, by inexperienced and prejudiced engineers.

It is a mooted question whether depreciation should be considered as one account, of which wear and tear, obsolescence, accident and inadequacy are all separate classes, or whether maintenance and repairs should be considered separately and depreciation used merely in reference to other class of deterioration. The objection to dividing the item is that it is difficult to say when repairs and renewals are maintenance or depreciation. As a matter of fact, all wear and tear requires renewals, the distinction usually being, that when the renewals are small as to parts or in cost, they are charged to maintenance, and when relatively large or expensive, they are charged to depreciation. Such classification is purely arbitrary and in any system consisting of a large number of parts and the investment of many millions of dollars, all renewals can properly be treated as wear and tear. The cost of such replacements do not affect the income any more than does the wear and tear account affect the income of a company having fewer parts and smaller investment. Many companies are following the procedure (which is simpler and ordered by some Public Service Commissions, and therefore, in the opinion of the speaker, preferable) of establishing in advance, an annual amount, which is set aside for depreciation of all classes, usually appropriating

this out of revenue month by month. This depreciation account is then charged month by month with the actual expenditures made for maintenance, repairs and renewals, the balance being carried forward as a depreciation fund. This method of accounting avoids the constantly occurring and irritating question as to which account, maintenance or renewals, the particular item being renewed, is properly chargeable. The importance of having a definite and uniform rule for charging maintenance and depreciation is at once apparent to anyone who is attempting to compare classes of expenses in two or more plants. In any case the proposal to periodically check and adjust the annual amount set aside to cover depreciation is to be commended and is being done by some corporations.

It appears to be unjustifiable on the part of the authors of this paper, to use 5 per cent as the basis of return on capital invested, even by way of illustration. The curve, Fig. 1, showing the cost of power, based on a 5 per cent return, is misleading, as no utility company can secure funds on any such basis, and the authors' own company very properly insisted upon and recently obtained a return of practically 8¾ per cent (including about one per cent for amortization) on its investment in the New York subway, and the State of Tennessee this week has had to pay 6 per cent to refund its public debt. Why, then, should such an erroneous figure as 5 per cent be used?

In fact, any return on the investment in mere physical property, as apparently proposed by the authors, is entirely insufficient and unfair, if "total production costs" are being sought; the proper intangibles or overhead capital expenditures should be included in order to obtain total production costs.

Item No. 28 defines load factor in relation to the maximum one-hour load; this is a longer period than would be accepted by many operators, as fifteen minutes, five minutes, or even less is frequently the basis on which load factor is estimated. The statement that the cost of labor varies with the load factor, reaching a minimum at about 25 per cent, would undoubtedly depend to some extent upon the size of the plant and number of units. It would seem that the statement that the cost per kw-hr. output varies approximately as the inverse fourth root of the load factor, should be amplified so as to show actually the conditions under which this rule has been found to apply, size of units, capacity of station, fuel and labor costs, etc., and what variations from these conditions are known it is possible to make without appreciably affecting the rule.

With reference to the paper as a whole, the question may be raised by some as to whether the subject discussed is a proper one for consideration by a scientific engineering organization. The speaker desires to go on record as endorsing the presentation of such an eminently practical engineering paper before the Institute, and further to acknowledge an obligation to the authors for the enunciation of their inverse fourth root rule,

which it is hoped will be found to apply, at least approximately, for all stations.

Carl Schwartz: Messrs. Stott and Gorsuch begin their paper by saying, "the need of some uniform method of accounting for the determination of the cost of power in steam plants has been long felt."

There is no doubt that this need exists because it is not alone difficult to draw a direct comparison between the cost of power from stations operating under different conditions, but in some cases even between two stations in the same locality, using practically the same kind of coal and operating under similar load characteristics.

The speaker is connected with a company which has for several years exchanged power station operating costs with other companies and knows that this exchange has been of benefit. In one case the cost of current for operation and maintenance of a modern power generating station containing four 5000-kw. units has been reduced from 0.67 cent in 1908 to about 0.45 cent per kw-hr. in 1912. It is true that the output of this station has increased from about 40,000,000 kw-hr. to about 76,000,000 kw-hr. per annum in the same period, and the average cost of coal has been reduced by about 11 per cent, still an appreciable amount of the reduction in cost of current can be attributed to the knowledge of other station performances. The cost of current at the present time is not as low as in some other stations of larger capacity; still, considering the price of coal, and the fact that the turbo-generators have a steam economy of about 18 lbs. per kw-hr., it is believed to be nearly as low as it can consistently be expected. If the steam economy of the turbo generators were 13 lb. per kw-hr. the cost of current would be about 0.37 cent.

The paper covers the elements entering into the cost of power in a comprehensive manner and gives a complete analysis of the conditions to be considered. The following comments are believed to be applicable.

A comparison of the cost of power should be made as simple and short as can consistently be done in order to relieve the operating companies of unnecessary accounting and computations, as otherwise some companies may decide that the expense of keeping their accounts in the manner prescribed and making the computations to bring their operating and maintenance costs on a comparable basis, exceeds the expense they feel justified in incurring. The more companies can be found to contribute to the statistics, the greater will be their value, and it would be unfortunate if all contributions to the cost statistics that are possible to secure could not be obtained.

A high degree of accuracy in making comparisons of station performances is desirable, still, some expenses cannot readily be compared, and for this reason it may be permissible to sacrifice a certain degree of accuracy for simplicity.

On pages 1620 to 1622 the items of production costs and production repairs costs are covered in full detail. To make a comparison between two or more stations it would seem that many of the items enumerated could be consolidated. If differences occur an investigation would readily reveal the reason and thus burdening the regular reports with a relatively large number of detail items of minor importance would be avoided.

Item PA, Management and Care, appears as an operating charge only. Some of the items thereunder, however, are chargeable likewise to maintenance and while the proportion chargeable to maintenance is small, still room should be provided for management and care under production repair costs.

The costs of the various items of production and production repairs are shown in cents per kw-hr. output. Some of these figures may not exceed a few hundred dollars per year and expressing them in cents per kw-hr. would take considerable time to compute and require many decimals.

I would ask Mr. Stott whether he sees any objection to the use of the total costs in dollars and cents for the detail items, making the distribution in cents per kw-hr. in the summary only, as given at the top of page 1623. An additional comparison would be afforded by expressing each of the items in percentage of the total.

Injuries to employees and other personal injuries and property damage is covered by group PJ-General, c and d. In investment costs, group IC, insurance covers the settlement of claims for personal injuries and property damage. Thus, accidents are charged against the operating account or to capital account, depending on whether the company carries insurance or not.

Fire or accidents will influence the cost of power from a station carrying insurance to the extent of the cost of insurance and from a station not protected by insurance will be correspondingly less, except in case of fire or accident, when the cost will be suddenly increased.

The accounts of a company carrying insurance and another not carrying insurance would, therefore, not be strictly comparable unless the condition for each station is made clear.

Mr. Stott covers very fully the matter of amortization and divides these charges into; first, physical depreciation, and second, functional depreciation. Physical depreciation is disposed of by charges against maintenance under the assumption that the plant will be maintained at 100 per cent efficiency.

For functional depreciation a comprehensive method is outlined which permits a readjustment from time to time to either make allowance for changes and additions or to correct certain assumptions as to the life of apparatus and machinery, should there be reason for doing so. While the flexibility of the method may be attractive, still it involves considerable labor and as an estimate of the life and the scrap value of the apparatus largely depends on the judgment of the person making the estimate, discrepancies are apt to occur which tend to offset the

advantages the method otherwise offers. Furthermore, the total life of 75 years for buildings may be impaired by radical changes after the shorter life of the machinery expires.

For comparing functional depreciation in place of this method, and for the sake of simplicity it is suggested to consider an average life of 30 years for the entire station and after making a deduction of 5 per cent for scrap value, charging a sufficient amount annually to equal, with interest compounded annually at 4 per cent, the prevailing investment.

By prevailing investment is meant the original cost of the plant complete excluding land but including all expenses chargeable to capital cost, like discount on the sales of securities, interest during construction, tests, preliminary operation engineering and contingencies. To this to be added annually the cost of additions and betterments less the original cost of any apparatus removed.

While it is realized that almost any form of depreciation offers room for objections, still it is believed that if some definite method like the above could be agreed upon and used as a basis for all comparisons of power station costs it would greatly simplify the work.

Referring to the Analysis of Production and Production Repair Costs, item 9, "average daily wages per man"—to compare the costs per kw-hr. net output of two independent plants on the same basis, a reduction factor is to be applied to labor only, the difference to be added to or subtracted from the total cost of production plus production repairs per kw-hr. net output.

This method would adjust differences in the cost of labor of different localities. It seems, however, that it would not allow adjustment in case the average daily wages per man are higher or lower by a different class of labor employed. For instance, one station may burn hard coal and be equipped with hand-fired grates requiring a certain number of men. Another station may be equipped with automatic stokers reducing the number of men in the boiler-room to a minimum though the average wages per stoker operator are higher than per ordinary fireman, thus raising the average cost per man for the entire station.

As to the reduction factor for labor, I have in mind the conditions of two stations, one burning soft coal with automatic stokers and the other hard coal screenings on hand-fired grates. The cost of labor and coal at these stations for the year 1912 compares as follows:

	Stokers.	Hand-fired-grates.
Net output, kw-hrs	83,000,000	47,000,000
Boiler room labor, per kw-hr	0.042 cts.	0.0984 cts.
Coal, per kw-hr	0.314 cts.	0.3127 cts.
Cost of coal per 2000 lb	2.37	1.63
Coal per kw-hr	2.66 lb.	3.8 lb.
Total operation and maintenance	0.492 cts.	0.593 cts.

The cost of labor per kw-hr. in the station equipped with hand-fired grates is over twice as high as in the station equipped with automatic stokers due to the greater number of men necessary for hand-firing.

The average cost per fireman is less than per stoker operator and this condition, if Mr. Stott's method was followed, would lower the average for the entire station force.

I am not sure whether a method can readily be found to make an adjustment in satisfactory form and the reason for calling attention to these possible inaccuracies is not to suggest further refinement but rather to suggest simplification in the method of comparing the cost of power, even if some accuracy has to be sacrificed.

The curves in Fig. 1 of the paper clearly show the influence of the load factor upon the cost of power and those referring to the cost of production and production repairs appear to be sufficiently close to be used for bringing these costs on a comparable basis. While I believe that in this case, as in others, simplicity should be the keynote, still it will be difficult to find a simpler method that will give satisfactory results. After sufficient data have been collected it should readily be possible to adjust the curves and equations if necessary and, therefore, the method given by Messrs. Stott and Gorsuch should form a good basis for making adjustments for load factor.

Daily factor of load is expressed as:

$$\frac{\text{Actual net output for day of 24 hours}}{\text{Net maximum hour's load} \times 24} \times 100$$

and it is stated that load factor based upon the rated capacity shows a wide amount of variation, and for this reason it is proposed to base the load factor upon the actual maximum one hour load.

To deliver the maximum load a certain number of machines is required and their capacity may or may not agree closely with the load to be carried.

The load factor could readily be expressed by:

$$\frac{\text{Net output in kw-hr.} \times 100}{\text{Generator capacity running} \times \text{machine hours.}}$$

It is believed that this method will give more comparable results because the investment and the costs of operation and maintenance have less relation to the maximum hours load than to the capacity of the machines and their time of operation.

To adjust for the relative value of coal a method is proposed which corrects for the difference in B.t.u. the cost of coal and the percentage of ash.

There are other factors entering into the value of coal, namely, volatile matter, which may curtail the capacity of the furnaces by producing excessive smoke, sulphur, lime, iron and silica which may increase the operating labor and furnace maintenance, and the percentage of ash and amount of clinkers enter into the cost of ash removal.

Not all of the above items may be of sufficient moment to require adjustment, but some of them it would seem should be taken into consideration in comparing performances, because some plants may give better results than others though the figure of merit for coal, if computed on the basis suggested, is the same.

Section III covers General and Miscellaneous Administration expenses which is proposed to be charged to the cost of power in the proportion the total operating and maintenance cost of the power plant bears to the total running expense of the corporation.

With some companies a steam power plant is a relatively small item of its business and the distribution of the general and miscellaneous administration expenses as outlines will be difficult. It would be better to omit all of these items, because they do not affect the comparison of the cost of power sufficiently.

The scope of the program of comparing the costs of power could readily be extended to cover not alone the cost of power at the busbars of the power stations but up to the third rail shoes or overhead collectors of electric locomotives or the customer's meters of electric lighting companies.

The summary of a form for operating and maintenance costs from power stations to the third rail which has given satisfactory results is shown below:

Items.	Total cost	Cost per kw-hr.
Power Stations:		
Net a-c. output, —— kw-hr.	....	....
Operating labor,		
Operating material,		
Maintenance labor,		
Maintenance material,		
Total at power stations,		
(1) *Total at Train Shoes,*	....	
Substations:		
Net d-c. output, —— kw-hr.	....	....
Operating labor,		
Operating material,		
Maintenance labor,		
Maintenance material,		
Total at substations,		
(2) *Total at Train Shoes,*	....	
Cable Department:		
Alternating current:		
Total a-c. input to subs., etc., —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total a-c. cables,		
(3) *Total at Train Shoes,*	....	
Direct current:		
Total d-c. output at third rail, —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total at Train Shoes,		
Third Rail:		
Total d-c. output at third rail, —— kw-hr.	....	....
Maintenance labor,		
Maintenance material,		
Total at Train Shoes,		
Grand Total at Train Shoes,		

(1) This figure to be obtained by multiplying the cost per kw-hr. at power station by 100, dividing by efficiency in per cent from power station busbars to train shoes.

(2) This figure to be obtained by multiplying the cost per kw-hr. at substation d-c. bus bars by 100, dividing by efficiency in per cent from d-c. substation bus to train shoes.

(3) This figure to be obtained by multiplying the cost per kw-hr. at substation a-c. bus bars by 100, dividing by efficiency in per cent from a-c. substation bus to train shoes.

The fixed charges for transmission lines, substations and third rail could be handled in a similar manner as for power plants.

The above can be briefly summarized as follows:

1. Condense the comparison and simplify the accounting and computations as far as possible.

2. Space should be allowed under the maintenance account for certain expenses under management and care chargeable thereto.

3. For all detail items total cost figures could be used instead of cents per kw-hr., to save labor and avoid small decimal fractions. The cost of items in the summary if expressed in per cent of total would permit additional comparison.

4. Simplify the method of calculating functional depreciation.

5. The average daily wages per man are not only determined by the cost of labor in different localities but also by the nature of the equipment and the class of labor employed.

6. To express load factor the following expression is proposed:

$$\frac{\text{Net output in kw-hr.} \times 100}{\text{Generator capacity running} \times \text{machine hours.}}$$

7. The figure of merit and reduction factor for determining the relative value of coal is believed to require additional adjustment. If a certain quality and cost of coal could be agreed upon as standard, comparison should be facilitated.

8. It is suggested to omit Section III, general and miscellaneous expenses.

9. The scope of the comparison of the cost of power could be extended to cover the cost of current up to the point of consumption.

In closing, the speaker wishes to express his belief that the authors' paper covers the subject so fully that with relatively minor revisions it should form an excellent basis for the Standards Committee as a standard method of comparing the cost of power.

William McClellan: It seems to me that this paper must be taken, as the authors have suggested, by a committee of the Institute and gone over line by line. More simplicity appeals to me; certain mechanical features about the report,

such as a better choice of letters, corresponding to classes, I think, can be somewhat improved.

Inasmuch as I have had some experience with public service commissions from the commission side, I must say in answer to the fear that the companies will object to doing the various things which are suggested in this paper, that there are two answers.

First, the companies themselves are finding out that there is nothing to object to. A number of companies in New York City are comparing costs with each other, and the result of this comparison is more or less public, but not entirely so. In the second place, companies will have to do it sooner or later.

The desirability of this sort of thing is, first, that we want it for ourselves—the companies themselves need it. A man who does not know just what he is doing in the way of costs in the production of power is not running his business properly. In the second place, the man who is not able to compare what he is doing with what the other man is doing, cannot make proper progress. First, it is necessary to know what we are doing for the sake of having the knowledge, and secondly, to compare our operations with those of others, which is important in all departments of life. Otherwise we cannot tell whether we are moving or not, and especially whether we are moving in the right direction.

I like the general plan of the paper very much. I think the Institute has had a tremendous lot of work done for it of the very highest quality. Just where certain items should be placed, I think there is a little doubt. When I first read the paper, I wished for educational purposes that depreciation could be put among production costs. Many men fail to realize that depreciation, or amortization, if you please, is an expense. There are many men who say: "Why should we take part of our profits and put them into depreciation?" The reply is that you are not earning profits until you have paid for every item you require in the operation of a plant. When the machine is operated, it is burning up just as surely and certainly as the coal under the boiler. You do not see it going on in just the same way, but it is as surely taking place.

One of the speakers spoke of calamities. If a building is destroyed by fire, I do not know how far you will be able to go into a depreciation fund for that. I think from the viewpoint of modern methods you would be unfortunate if you did not have insurance on the building.

Take the division of depreciation into large and small repairs. It is an operating expense. There is a question if you reduce these things into a formula, as to what effect it will have. You may pay for the repairs directly out of this year's operating expenses, or you may defer them and pay them five years from now in the form of larger repairs. That is a matter of bookkeeping, but when you introduce depreciation into a formula

and have the results comparable with the results of other companies, it does make a difference, and that would require a great deal of thought.

Companies must be put in different classes, or you will not be able to compare them justly. It would not do to compare a small station with a large one, or one station with another station of a totally different type. Therefore we must put the stations, or whatever we are comparing, into various classes, so that they can easily be taken care of.

Finally, I want to make a motion, Mr. Chairman, if I may. It has been suggested by the authors, and in following out their wishes I desire to move that it be the sense of this meeting that the suggestions made in this paper be referred to the Board of Directors of the Institute, that they may refer it to a proper committee for immediate action, the meeting believing that it is extremely important that the subject be brought as soon as possible to a practical basis for use by the Institute members.

C. O. Mailloux: I take pleasure in seconding the motion. I consider that the Institute is to be congratulated again in having a paper of this kind from Mr. Stott. It is especially to be congratulated upon the fact that all of Mr. Stott's papers on central station economies have been read before the Institute. You do not appreciate that now so much as you will a few years from now, when you look back and see the evolution of central station economics and come to realize that Mr. Stott is the man who really put the matter on a sound basis. Some of his papers will then be recognized as classics and we will appreciate their value. A few years hence engineers will look upon Mr. Stott's papers with the same high respect that is shown the classic writings of Rankine.

I think it is very important, as Dr. McClellan said, that this paper should be put in the hands of an intelligent committee especially fitted and qualified to deal with the many questions which the paper brings up, so that the valuable data and information contained in this paper may be put in such form that it will be made available to the Institute members and to the profession of engineering in general.

Peter Junkersfeld: I feel that too much has, perhaps, been attempted. However, as Mr. Stott has said, the matter is presented as a target, and with that explanation, it is very well put, indeed. If this paper is referred to a committee in accordance with the motion pending, I would suggest that such committee look over the field carefully and see what has already been done in this connection.

We must not assume that no standardization so far has taken place. I would call attention to the fact that both the National Electric Light Association and American Electric Railway Association have a standard classification of accounts, and as far as power house general classifications go they are practically the same. The National Electric Light Association has nine

general headings for the power house expense and the American Electric Railway Association eight. I have here a memorandum showing the number of subdivisions under the various headings of power plant expenses as divided by the Commonwealth Edison Company, which follow closely the National Electric Light Association; those proposed by Messrs. Stott and Gorsuch; and those proposed by the American Electric Railway Accountants Association. (See table on next page.)

The most important thing is to consider the general headings, say eight or nine, so that when we compare these in different plants we will know what we are talking about. If we find a discrepancy, then we can analyze and subdivide, but the subdivisions must, in many cases, be different, because there are many local conditions that will affect one place as compared with another, but the general headings ought to be alike.

There are many details which might be discussed. One very important point made was that the net output should always be considered and not the gross output. It is surprising how many people throughout the country make that error. It is obvious that it is not worth any further discussion. Net output, in my judgment, should always be used, and there is no excuse for using gross output.

So far, I am speaking entirely of operating cost. Now, on the investment side of the business, standardization is going to be more difficult, and, I would suggest, as a matter of practicability, and of making the most headway, that your committee concentrate its efforts, first, on comparison of operating costs.

I am afraid if they attempt to standardize the entire thing at one time, they will meet with opposition in different parts of the country. There are many conditions all over the country where, if a company should show all its investment costs, it might be subject to difficulties from people who, through ignorance, or through intent, might misuse this information.

It is possible, also, to segregate general expense a little too far in that connection. You cannot in any line of business, whether it is a central station lighting company or a traction company, assume that the power house is an absolutely independent business by itself. Therefore you must have some general expenses which cannot be apportioned correctly. You can approximate them, but to say as a matter of record, that month by month so much should go against that station, and so much against another, is not always getting at it in accordance with the actual condition. There may be some extraordinary work, or some contingency, that will involve one power house a certain length of time. During this time any general expense you ordinarily apportion to that power house would be far too low, and when that state of affairs occurs you are fooling yourself. General expenses do not have a constant ratio to each of different elements of the business.

Load factor is very important, and I am glad the authors

CLASSIFICATION OF POWER PLANT EXPENSES.

Commonwealth Edison Company	Proposed by Messrs. Stott and Gorsuch	American Electric Railway Accountants' Association
	Management and care: 10 Subdivisions.	
(1) Labor for operation: 6 subdivisions.	Boiler Room Labor: 12 subdivisions. Engine room labor: 7 subdivisions. Electrical labor: 9 subdivisions.	Powerhouse operating labor: No subdivisions.
(2) Fuel: 5 subdivisions.	Fuel: 7 subdivisions.	Fuel: No subdivision.
(3) Water: No subdivision.	Water: 6 subdivisions.	Water: No subdivisions.
(4) Lubricants: No subdivision.	Lubricants: 2 subdivisions.	Lubricants: No subdivisions.
(5) Station Supplies and expenses: 7 subdivisions.	Production supplies: 7 subdivisions. Station expenses: 4 subdivisions.	Power plant supplies: No subdivision.
—	Operating general expense: 5 subdivisions.	—
(6) Maintenance and repairs of station building and property outside of station building: 4 subdivisions:	Building repairs: 6 subdivisions.	Building repairs: No subdivision.
(7) Steam equipment repairs: 8 subdivisions.	Repairs to furnace and boilers: 10 subdivisions. Repairs to boiler accessories: 8 subdivisions. Engine repairs: 5 subdivisions. Repairs to engine accessories: 5 subdivisions. Repairs to piping: 10 subdivisions: Repairs to tools: 4 subdivisions.	Equipment repairs: No subdivision.
(8) Repairs to electrical: 4 subdivisions.	Repairs to electrical generators: 5 subdivisions. Repairs to electrical accessories: 8 subdivisions.	
—	Repairs general expense: 4 subdivisions.	—
(9) Purchased power: No subdivision.		Purchased power: No subdivision.

SUMMARY.

	General Headings.	
Nine.	twenty.	Eight.
	Subdivisions.	
Thirty-four	One hundred and thirty-four	None.

brought it up. They have pointed out that there is a good deal of misunderstanding all over the country as to load factor. Every time load factor is used it should be stated whether it is daily, monthly or annual load factor, and what kind of peak it is based on. In dealing with load factors and maximum demand, we should be very definite and know just what we are using, know that it is not guess work, something really substantial, an actual observation of all the elements that make up load factor.

In figuring investment costs, spare capacity is a big item. You may be able to operate under certain conditions with 10 per cent spare capacity. Under other conditions, with a growing business, that may be much too close. I know of situations where 20 per cent is too close, because of the rapid growth of the business. That does not mean the company always carries 20 per cent, but that is the figure when everything goes well. If there are labor troubles or manufacturing difficulties, that 20 per cent in one year may go down to 5 per cent. Such possibilities must be provided for.

As to maintenance and depreciation, these items often do not tell the whole story. If a man has a very low maintenance account it is well to look back of that account and see what his machinery looks like. We must consider very definitely both maintenance and depreciation when we speak of these terms. When we look over the past, it is one matter to assign a certain amount for depreciation, but when we look ahead we do not know what it is going to be, and we must allow a reasonable amount to cover what it may be. Past and future depreciation are two separate things and should never be confused.

D. B. Rushmore: The cost of power is the basis of nearly all engineering work. Practically everyone is manufacturing something in which a cost comparison is the basis for decision between different paths of action.

The specific point under discussion this morning is one phase of a very general subject that includes the cost of articles manufactured in practically every walk of life. The farmer is manufacturing his products, the railroad man manufacturing transportation, the electrical engineer manufacturing electricity, or whatever else it may be, and the very fundamental part of this engineering work is the cost of the product. This cost is generally recognized as being divisible into a quantity which varies according to the output, and when the consideration of this specific case comes up during the coming year it will be of interest to those working on it to consider the broader underlying fields which are necessarily involved.

The usefulness of this paper at the present time is not only to operating men, but also to a field in which the speaker happens to be engaged, that of manufacturing companies. At the present time the difference between hoisting by compressed air or hoisting by electricity is very largely one of the cost of the output,

and the basis of comparison is not very easy. It is very difficult to get the advocates of different systems to agree regarding the items which should enter into the comparison, and until such a decision is reached it is very hard to play the game in a proper way.

In connection with the amortization, there is a different class of amortization in the general field involved in those pieces of machinery and in those products which have a natural life. An incandescent lamp has a limitation to its usefulness which is more or less fixed, a motor approaches the dividing line. We expect to wear it out and throw it away. Larger machinery does not wear out, but individual parts do, and a few parts can be replaced and the condition of the machine kept up to its original shape.

The fact that up to the present time it has been very difficult to determine the actual costs of power for different plants and operating conditions, represents a condition fully justified by the fact that for a concern, individual or company, to give out its manufacturing cost, it must be in a position where these cannot be used to affect its condition adversely, and the advent of the Public Service Commission, with the protection that it gives, along with its other features, is one of the reasons why it is now permissible to give more publicity to these figures. A suggestion is made for the coming year that in order to get the most benefit from the tree which is going to grow from this seed planted by Mr. Stott and his associate, that an effort be made to bring the engineers of the Public Service Commission into the Institute and to have them in some way affiliated with that part of the organization which will be active in formulating these principles.

L. P. Crecelius: The abstract of this paper begins with a statement that power cost should be upon a basis of per kilowatt-hour net output. This looks like a good beginning, and the same principle as laid down here should be applied to every one of the various groups which follow.

In the case of I, Production and Production Repairs Costs: The proposed method seems proper, but care should be excercised before adopting it as standard in its present form to avoid upsetting such existing classifications of accounts as are now standard, in extensive use and under which a multitude of reports are made to various local, state and national utilities commissions. Such little differences as appear in the treatment of the various accounts under this heading as presented in the paper are relatively unimportant and no great difficulty should be experienced in getting them in a proper shape.

In the case of II, Investment Costs: Exception is taken to the proposal of apportioning franchise and revenue tax and charging some of this expense out as cost of power. The reason for this will be given later. The miscellaneous item of this group is open to the same criticism, as will be pointed out later.

In the case of III, General and Miscellaneous Administration Expenses:

Under this group are a few items which may properly be charged out as cost of power, in the case of certain corporations, but on the other hand, it is proposed in this paper to charge as cost of power, a great many other items which in my belief cannot and should not be included.

The time is indeed opportune for the presentation of this committee report to the American Institute of Electrical Engineers with the request that it go before the Standards Committee, in fact it is past opportune, and I welcome the opportunity thus afforded to present my views on this important matter. There is no question before the power engineer which approximates in importance the question, "what is the *true* cost of power"? He finds himself continually confronted with this question, especially, when the proposition comes before him to decide whether it is wise to continue to manufacture power or whether it would not be better to purchase power from someone who has the peculiar gift of making it cheaper. Again and again, in working up this case little or no information is at hand and rarely can anything better be found to substitute imaginary estimates in order to secure the significance of the value of a great many obvious but ordinarily obscure items such as, for instance, administration expense, casualties, extraordinary maintenance, etc. The greatest use to which this method of determining and comparing costs in steam plants will be applied is in connection with extensions and betterments to existing power plants, and in the matter of determining a proper basis for the purchase of power. Therefore, let the method and its arrangements be such that the true cost of power will result.

My objection to the proposal of permitting much of the general and miscellaneous administration expense of a corporation other than a purely power producing concern to be charged out as power cost is based simply upon this illustration; a railway company operating power plants, is in need of betterments for extensions or otherwise, and is at once approached with the subject of purchasing power. An analysis of its present cost is made and compared with other plants for such information as is available and the possibilities of the betterments as reflected upon the future power cost are brought out. Now, however, if the cost of power is found upon the basis proposed in this paper, it is burdened with a great many foreign miscellaneous expenses such as the salaries of executive officers and the presidents' or directors' travelling expenses to a convention, a portion of which is here proposed to be called power cost; the chief counsel's expenses in connection with appearing before a utilities commission on some question other than power, is also called power cost, and so on. When all these items are added to the cost of power under this plan, it is decided to purchase power rather than to make additional

investments, and the old equipment is scrapped and written off the books. The result: it is soon discovered that the administration, general and miscellaneous expenses still continue with the corporation which now purchases its power; no reduction in these items is noticed; an allowance for this expense has been made in the cost of the purchased power and we now find the situation where for a great many years the railway is obliged to pay this expense doubled.

The ready means which were at first available to relieve itself of a portion of the expense of these items on the score of power cost as had been practised before shutting down its power power plants, are now gone; secondly, the railway has permitted this previous expense which was called power cost, to be added to all the power which it now purchases. In the face of this situation, my suggestion is, first, that a good rule to follow with reference to these miscellaneous revenue and income tax expenses, administrative office and miscellaneous expenses, is to charge only that portion which would disappear in the event that power was purchased, and secondly, that the report as presented by this committee should receive more consideration in this respect, again going before a committee and every angle of this complex subject being carefully analysed.

W. G. Carlton: The summary of operation and maintenance costs or as called by the authors, the "Production and Production Repair Costs", is sufficient for moderate size power stations without going into all of the detail given on pages 1620 *et seq.* A monthly comparison on substantially the same basis as this summary has been made for several years by six electric power stations in and near New York City; these power stations having monthly outputs ranging from 2,000,000 to 18,000,000 kw-hr. This method was shown by Mr. B. F. Wood in a paper on *Electrical Operation of the West Jersey and Seashore Railroad*, presented at the annual convention of the Institute at Chicago in 1911.

In addition to giving the unit costs per kw-hr., it is frequently convenient to have the total cost stated, especially in the smaller items, since a better idea of their importance can be grasped from the total money involved than from the unit costs.

August H. Kruesi: This paper will be the more rapidly adopted and be more valuable the more general it is made. I recommend that its scope be extended to include those electric light and railway companies which also produce steam for heating, of which there are a large number in this country. The method would then be applicable to a very large number of industrial power plants which not only produce electrical power, but exhaust steam for heating, and live steam for manufacturing.

I believe in connection with the comparison of costs that the load factor is not sufficient; that we ought to take into consideration not only the machine load factor, but what we may call the station capacity factor. We might divide both the max-

imum load and the monthly output by two and still get the same load factor, but a large part of the operating cost per unit of output would be twice as great, the fixed charges per unit of output twice as great, and the costs tremendously affected.

The proposed inverse fourth root relationship is represented by curves as shown in the paper, or as in Fig. 2 herewith. I suggest that instead of dealing with the costs per unit of output we should deal with the total output and the total cost. The relationship is then represented by an approximately straight line as in Fig. 1 herewith. This I think will facilitate comparison

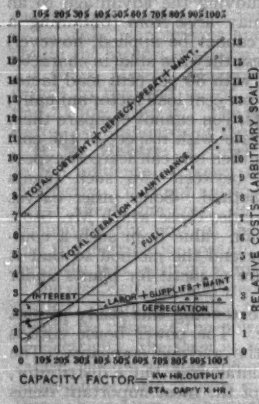


FIG. 1—RELATIVE COSTS FOR 4000-KW. POWER STATION

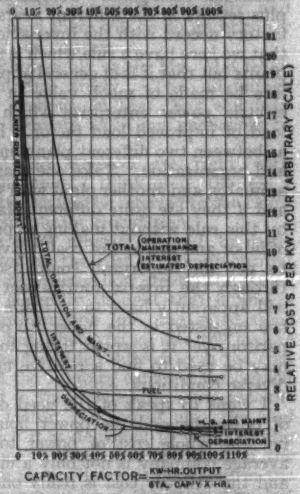


FIG. 2—RELATIVE COSTS FOR 4000-KW. POWER STATION

and will be more readily understood by the accountants and the executives who have to deal with such questions, as well as by the engineers. If it is desired to deal with an equation rather than by plotting, Fig. 1 permits an equation which is much easier to use. The actual performance of a certain steam turbine station is represented by Figs. 1 and 2. Whether the plotted results will always lie on a perfectly straight line or not does not matter and does not make the method suggested any less accurate than the proposed inverse fourth root method.

D. C. Jackson: This communication of Messrs. Stott and Gorsuch is an important addition to the extended series of

truly classical papers which have been produced by Mr. Stott and his assistants. There are two quite distinct and yet closely related features in this paper. One is the proposal that suitable records shall be kept by power companies, and the presentation of a method of keeping them. The other is the statement of Mr. Stott's new inverse fourth root rule of the cost of power as it is affected by load factor. In respect to the latter, I have made some tests of the application of the rule to certain relatively small generating stations which have enjoyed a steadily improving load factor for a number of years and in which the supervision has been good. Comparing the cost of power production plus repairs in the different years, the results come out in satisfactory accord with the inverse fourth root rule, which indicates that we here have a rule which is not only applicable to enormous plants but that it is of general applicability. The rule may therefore be made of much value in studying the advantage to an electric power enterprise which may arise from obtaining a load of improved load factor. It cannot be applied, however, as between two different plants unless they are alike in character and organization. Take one plant with 30 per cent load factor annually, and another plant with 45 per cent load factor annually, and if they are quite different plants, you cannot compare them by this rule without making a prorate with respect to the cost of labor and the cost of coal. Even then one can scarcely expect to get an important comparison between two such plants through the inverse fourth root method. Some other curves will apparently have to be made besides those which Mr. Stott has suggested in the paper, to obtain value from such a comparison, yet it is worth trying to extend the method so that it may be used to find a relative figure of merit for plants under diverse conditions.

I want to speak of the need of extending this study of cost of power beyond the power house. The power house cost is not the whole cost of power to the average company. The average company is not only a manufacturer, but a distributor, and the delivery cost is really one of the most important items in a large number of cases. In fact the delivery costs may be greater than the production costs, and under these circumstances we should not be satisfied to stop at a study of power house costs. This is a problem that needs the joint consideration of the engineers and the auditors, and until such coöperation is brought about in our electric companies, power costs will not be fully figured and known and the lowest profitable prices which can be made for classes of customers will not be determined.

I will not attempt here to go into the details of this paper. A classical paper does not ordinarily lend itself to discussion in detail; and this paper like its type is a stimulus to study rather than discussion.

Ralph D. Mershon: Professor Jackson is in favor of extending the study of power costs to the distribution system. Before doing so it would be well to agree as to the meaning of some

of the terms usually employed in such a discussion. For instance, we should have an authoritative and acceptable definition of "load factor." As it is now, when a man talks about load factor one cannot be sure just what he means. Some persons associate the load factor with the station, making it depend upon the load in relation to the rated capacity of the station. To my mind the load factor is a characteristic of the load and has nothing to do with the station. The Institute has a definition of load factor, but this definition is far from being definite, and does not appear to be acceptable to other electrical organizations. The endeavor should be made to give the terms we employ such definitions as will be acceptable generally, and so explicit that when a term is used there will be no uncertainty as to the meaning it is intended to convey.

P. W. Sothman: I agree thoroughly with Mr. McClellan that we should publish statistics freely. The advantage gained from statistics is very obvious, in that they will help us to make comparisons and stimulate us in our endeavors to obtain the highest efficiency.

I think Messrs. Junkersfeld and Mershon are right with regard to the load factor. The more I think of it, the less I find I know about it. The matter should be referred to the Committee on Standards of the Institute for elucidation.

H. M. Hobart: I think a brief allusion should be made to the influence of power factor on the cost of manufacturing electricity. It is apt not to be recognized how greatly the power factor affects the cost. It is generally thought that it affects exclusively the cost of the transmission line, the substations and the distribution system. But when you go into the matter seriously you will find it makes a decided difference in the cost of the electricity as delivered at the outgoing cables of the central station. I am of opinion that in these schedules some account should be taken of the power factor. Of course, also, the *kind* of electricity, the *form* in which it is delivered to the outgoing cables, makes a large difference. When it is delivered in the single-phase form it costs more than when it is delivered in the three-phase form. The turbines may be of the same size, but when you take into account the increased size of the generators and their lower efficiency when designed for single-phase, it is found to make a very decided difference. The difference is apt to be confused with the circumstance that this single-phase electricity for the purpose for which it is now required on a large scale is always associated with a low power factor. The aggregate result of being required to deliver the electricity at a low power factor, and at the same time in the single-phase form, is to occasion a very serious difference in the cost of electricity, which certainly must be taken into account. It is utterly erroneous to consider that the two kinds of electricity can be produced at substantially the same cost.

I was glad to notice in the paper and also in the discussion the increased tendency to express the capacity of the station

in terms of the millions of kilowatt-hours per annum to be delivered, rather than in terms of the rated capacity in kilowatts, because when you come to the rated capacity in kilowatts it is difficult to apply a definite rating to a station. In looking into the matter of the thermal regulation of turbo-generators, one finds that a large generator which will deliver an output of unity for a given ultimate temperature of its windings on the coldest day of winter, will have its capacity brought down to something like five-tenths on the hottest summer day, so that you can hardly put on the nameplate of the generator a rating in kilowatts, when it varies from two to one from the coldest day in winter to the hottest day in summer, provided you want to consider that the limitation to the output of the generator is the temperature of the hottest part of its windings.

Paul M. Lincoln: I want to make a few remarks on the matter of load factor. We have been told that when we talk about load factor we do not convey any idea of what we are talking about. I do not think that is exactly true. I might use, as an illustration, that if I should say I saw a dog on the lawn, you would know in general what I was talking about, but you would not know whether I was talking of a dachshund or cocker spaniel, or some other kind of dog. If I wanted to convey the idea of what particular kind of dog I was speaking about, I should have to say I saw a male cocker spaniel pup a few weeks old, having such and such characteristics. We are doing exactly the same thing, when we speak about load factor. When I say load factor, you know in a general way what I am talking about. It is a generic term, not specific; it is the difficulty with the speaker, as a rule, that he does not define exactly what he means. But if I should speak of the daily load factor, based on a fifteen-minute maximum, you would know what I meant, and if I should speak of a yearly load factor, based on a one hour maximum, you would know what I was talking about. The term "load factor" is perfectly defined in its generic sense, and if the speaker wishes to be more definite, it is up to him to put in the proper qualifications.

Ralph D. Mershon: Will your remarks apply to the case where the load factor is the ratio between the average load on the station and the generating capacity you have in it?

Paul M. Lincoln: That is not load factor, that is something else.

Ralph D. Mershon: Most people call it load factor.

Paul M. Lincoln: Load factor is something that applies to the load and not to the station that carries the load.

W. S. Gorsuch: The formula on page 1650 has been criticised by Mr. Floy, because "general and miscellaneous administration expenses" are not included. These items can be added in the same way as "Investment Costs," making correction for load factor only, as explained on page 1648. However, it is not the purpose of the formula to express the total cost of power but to show after applying correction factors the

relation of those costs which depend upon the station design, efficiency and management, as illustrated and explained on pages 1646 and 1647.

To compare two plants from a purely operating point of view, it is proposed to correct for the "Average Daily Wages per Man" and the cost and quality of coal or "Figure of Merit", as these two items are materially affected by local conditions over which the station manager may have little or no control. The other items of production and production repairs are practically factors of station condition, design and management and can be directly compared without making any corrections. The Investment and Administration Costs are independent of how a station is operated or managed, and these items can be compared directly on kw-hr. net-output basis without any corrections, to see whether or not either station is unduly burdened with such charges. One plant may be carrying more surplus capacity than is necessary and for which there may not be any demand in the immediate future. If a correction factor were applied to every item of cost, a hypothetical station would be set up equivalent to the plant taken as standard of comparison, with the natural result that the power costs for both plants would be practically the same.

I do not know of any life expectancy table that is generally accepted by engineers, as has been stated. Further, the life expectancy table used in the illustration is not given for the purpose of setting up a standard, for there cannot be any standard in the sense that the table is used in the paper. An independent life expectancy table should be established at the beginning for each plant and readjusted at certain periods. If two plants are equipped with similar apparatus and installed about the same time, the life expectancy tables at the start would naturally be the same. If, on the other hand two plants should be installed a period of years apart with similar equipment the life expectancy tables may be correspondingly different for certain apparatus. One company may purchase and install apparatus that will soon become obsolete while another company may have had similar apparatus in service for several years, in which case it would not be consistent to apply the same life expectancy table when each plant was put in operation.

In comparing the power costs of any two stations with a view to purchasing and interchanging power or combining plants, it is essential to see that the life expectancy tables are not relatively too low or too high. What the whole scheme really amounts to is to establish a reasonable independent life expectancy table at the beginning for each plant, so that the percentage estimated to be set aside will be sufficient to replace the apparatus when it becomes obsolete or inefficient.

The expenses of personal injuries, other property damages and pensions, chargeable to the power plant should be determined independently, as they are relatively small in comparison with those of other departments of a railway or lighting company.

These expenses may be incurred by straight operation or during repairs and it is proposed to charge them to production or production repairs as the case may be.

Mr. Schwartz seems somewhat apprehensive regarding the application of the "Reduction Factor" for labor when comparing a hand-fired with a stoker-operated plant. While it is true that there will be more men, and that the "Average Daily Wages per Man" may be lower in a boiler room that is hand fired than in one using mechanical stokers, yet it is equally true that one plant may have too many other classes of men in the station due to bad management, poor arrangement and kind of equipment etc. If it is desired to know what the stoker operated plant with its entire equipment can do, provided the lower price of coal and lower (possibly) "Average Daily Wages per Man" of the hand fired plant can be obtained, it will be perfectly fair to apply the "Reduction Factors" for coal and labor as outlined in the paper. It may be that a hand-fired plant has a lower "Average Daily Wages per Man" with practically the same "Figure of Merit" of coal as the stoker-operated plant with which it is being compared, in which case it will be necessary to increase the cost of labor of the hand operated plant for comparative purposes.

In reply to Mr. Schwartz's suggestion that in determining the "Figure of Merit" of coal, volatile matter, sulphur and other ingredients than that of ash should be considered. I wish to say that it would be very difficult to correct for many of the factors, and further, the variation of some is so small as not to materially affect the "Figure of Merit". For illustration, in comparing two coals it will require a difference of 30 per cent in hydrogen to make a difference of about 1 per cent in the "Figure of Merit".

Regarding the question whether it would not be better to give the total cost of each item under the various groups instead of the cost in cents per kw-hr. net output which in some cases will be a decimal of several ciphers, it will not be possible to compare corresponding items of two stations on the same basis unless reference is made to the kw-hr. net output.

The charges covered by Group P.A. "Management and Care" would naturally be distributed among all the other groups, but this would be very difficult to do, as some rule or assumption of distribution would have to be made which would vary for different stations. For comparative purposes it seems to be advisable to group these costs as outlined.

If the percentage to be annually charged to the "Amortization Fund" is determined by using the average weighted life and the total cost of the plant, it will be found after a period of years that there will not be sufficient funds to cover the required replacements. The proper way to arrive at this percentage is to determine the amount to be set aside annually for each main item as outlined in Table I and then determine the rate by taking the total annual charge and the total amount to be amortized.

Regarding the question as to whether the relationship between load factor and cost of production plus production repairs as expressed by the inverse fourth root law is applicable to small plants, this law will hold for plants of 5000 kw. capacity and probably smaller.

There seems to be a difference of opinion as to whether the "General and Miscellaneous Administration Expenses" should be included in the cost of power. For the purpose of comparing the cost of power from an operating point of view, it is not necessary. However, for the purpose of exchanging or selling power a portion of these expenses should be included in order to obtain the true cost of power to the company. A portion of the administration expenses is required to make and keep the plant a going concern, such as the purchase and distribution of fuel and material, drawing up contracts for materials and apparatus used in repairs, adjusting claims, relief, handling pay rolls, etc. Taxes are also imposed on the company for the privilege of operating.

Aside from the above, if a company desires to determine whether it will be cheaper to purchase power, it will be necessary to exclude such items that will not disappear and include those that will disappear in the event of power being purchased. This not only applies to "General and Miscellaneous Administration Expenses" but also to "Investment Costs". For instance, the bondholders may require that the plant be kept intact and not dismantled and scrapped. In contemplating the purchase of power, the conditions should be considered under which the proposition is made before comparing power costs, as items that will disappear in one case may not disappear in another.

I do not see that it is necessary for any classification of accounts that may be decided upon for determining and comparing power costs, to conform strictly to any Public Service Commission Classification. However, the grouping should be arranged so that any Public Service Report can be compiled from it.

The amount of the miscellaneous items in each group will be relatively small as any appreciable expenditure can be charged to a definite item.

E. D. Dreyfus (by letter): We have long felt the need of establishing criteria for measuring the performance of our power plants. If the movement Mr. Stott and his associate have inaugurated will be conducted in the manner it deserves, benefits to industries are bound to result. Some stations under efficient and progressive management have established results which should be fairly taken as bench marks from which other stations should measure their performance.

Conditions, of course, vary widely and the authors have focused attention upon those which were of the most serious nature and have proposed formulas to reduce the operating conditions of different plants to a more or less common basis.

In connection with the formula at the bottom of page 1648, it is the writer's opinion that in a great many plants there would be either difficulty or a great deal of additional work to adequately and satisfactorily determine the percentage of combustible in the ash. For simplification I would propose that this formula be modified so that the "figure of merit" could be ascertained directly from the coal analysis and the total effect of the percentage of the ash taken care of somewhat in accordance with the results obtained by Mr. W. L. Abbott in a long series of tests conducted in Chicago upon the effect of variation of percentage of ash in the fuel and which was published in the proceedings of the Western Society of Engineers, 1906. Also, I wish to call attention to the fact that the use of the long ton confines this formula, more or less, to sections in and around New York. I believe according to government reports that over ninety per cent of the coal mined is sold on the short ton basis.

The authors have adopted a factor termed, "The Average Daily Wages per Man". In this connection I might mention another point which might have some bearing, and that is that some operating companies work on a very much closer margin as regards the number of men engaged in running the power house than others. Some companies hold more men in reserve for emergency and figure that the cost of this insurance is worth while; while, on the other hand, other companies view the matter from the standpoint that it is best to keep the labor cost down to the minimum and economy thus effected will more than offset any probable loss due to emergency which might have been largely offset by having extra men working around the power house and in readiness to do emergency duty.

As the writer understands it, as far as the present analysis goes, it is probably the intention to compare stations of practically the same size. Although it might seem a difficult matter to establish a relative scale for plants of different capacity. I believe this phase could be worked out in a satisfactory and dependable way through a synthetical study. There will probably be times when it will be desirable to compare stations of different capacities regarding which the other operating conditions are very similar.

As is obvious, the question of power plant comparisons is to a large extent, involved, and the authors are to be highly commended for the steps they have taken to overcome the apparent obstacles and make comparisons of practical and definite value.

Charles S. Ruffner (by letter): The power costs of two given plants will differ because of size, cost of labor, fuel and other supplies, the average use of maximum load or load factor, the relation of maximum demand to total capacity, investment, efficiency of management, and the degree of proper coördination of each unit of equipment as regards relative capacity and location. The paper of Messrs. Stott and Gorsuch attempts to

compare power costs by eliminating or equating three of these variables, cost of labor, cost of fuel and load factor, with the obvious purpose of determining the last two, viz., efficiency of operation and efficiency of original design.

Like all comparative analyses of costs and efficiencies the problem is one containing so many variables as to make difficult a mathematical solution, and it has often been questioned whether the generalized results obtained by such studies justify the elaborate processes involved.

Comparative costs of generating electrical energy are, however, becoming of increasing importance. The determination of reasonable rates by regulating commissions raises the question of relative efficiency. The value of a water power, where such a separate value exists, involves the question of the financial economy of hydraulic generation over other available processes, and while the present paper relates to steam plants only, similar methods must be developed for making such comparisons of various types of generation. Large operating syndicates are in need of concrete methods of analyses for comparing the results obtained by the various plants under their supervision. The necessity of a comprehensive scheme of analyses for these purposes will outweigh the limitations of comparative methods such as those outlined in the paper.

The classification of accounts which comprises the larger portion of the paper is not essential to the scheme of analysis outlined. Central stations are generally operating under classifications recommended by the National Electric Light Association or the American Electric Railway Association or prescribed by state commissions. These accounting systems segregate the operating cost at switchboard from other operating costs and subdivide this general group into station labor fuel, miscellaneous operating expenses and maintenance items similar to those provided in the paper. While the proposed classification has many novel features it is not suited to all sized plants, does not take into account the possibility of the steam plant being used for other than steam generation purposes, evidently overlooks the impracticability of separately segregating general and undistributed expenses belonging to power costs from other portions of the business and introduces terminology much at variance with established practise. Present central station accounting methods have been gradually developed after years of experimentation and after consideration of the joint needs of the operating manager, the accountant and the engineer, and it is difficult to see what purpose will be accomplished by the changes contemplated. The accounts of any up-to-date electric utility permit separation into the items of Production Cost, Production Repair Cost and Investment Cost, the sum totals of which are used in the scheme of analysis, and will disclose the proportionate amount of expense burden applicable to these costs.

The most important feature of the plan outlined for compar-

ing costs is the load factor. The effect of load factor upon the investment costs is not difficult of determination since these costs per unit are an inverse function of the use. Question may be raised, however, as to the basis of calculating what the investment charges really are.

Interest and profit are inseparably associated in "rate of return" and few investors or bankers would finance a power plant with the expectation of receiving only a five per cent rate of return on their investment. It is true that money is often borrowed at five per cent interest for short terms or for long periods where the security is gilt edge, that is, with a substantial equity. The owners of the equity, however, expect larger rates of return than five per cent, either through the payment of interest or dividends or appreciation in market prices of their holdings. The use by engineers of low interest rates on the entire investment in calculating annual costs has contributed to the low regard in which capital "planted" is held today.

Considerable difficulty must necessarily be encountered when attempting to determine the proper amount to be set aside annually to cover that portion of investment charge represented by depreciation. The work of prophecy is an exceedingly difficult task at which to maintain a reputation for accuracy and has developed attractions since the world began. The man putting up his money cares little whether the unit of equipment requires abandonment on account of wearing out, obsolescence or inadequacy. He desires the engineer to advise him with respect to proper annual reserve which in the long run will reproduce his investment. Data upon which to predict such calculations are very meager and confined to a few instances, possibly not representative of the group or class. The accuracy of such calculations, even for a class, can not accordingly be very great, and herein lies another reason for estimating the cost of money at higher than ordinary interest rates, to at least in part compensate for the hazard arising out of the lack of knowledge of the probable life of units of equipment. The Institute has much work cut out for it along this line.

The effect of load factor upon the cost of operation and repairs is, however, more involved. This relationship, it is stated in the paper by the authors, may be expressed by the empirical formula

$$Y = s\,\frac{y\sqrt[4]{x}}{\sqrt[4]{X}}$$

where Y represents the cost in mills per kilowatt hour net output, X the corresponding load factor expressed in per cent, and y a constant for any curve. It is stated that "this law will hold between 15 per cent and 90 per cent load factors and is applicable for individual plants, but in comparing independent plants the cost of power in each plant should be reduced to a common load factor."

It would be fortunate if this important relationship could be thus simply expressed and the entire problem of station economy reduced to an approximate formula. It is observed, however, that the expression does not even generally fit the experience with which the writer is familiar. It does not account for variations in monthly costs with which the operator is interested and does not promise as great economies with better load factors as experience has proved are possible. Two typical instances, one condensing turbine operation and the other corliss condensing engines, may be cited as illustrations, and are given below:

Station A			Station B		
Monthly load factor.	Actual mills per sb. kw-hr.	Calculated mills per sb. kw-hr.	Monthly load factor.	Actual mills per sb. kw-hr.	Calculated mills per sb. kw-hr.
45	6.46	6.36	35	11.30	9.63
47	6.97	6.29	38	11.34	9.43
48	6.75	6.27	45	10.48	9.06
49	6.38	6.25	46	9.62	9.02
50	6.20	6.20	47	10.41	8.95
52	6.02	6.16	48	9.56	8.93
54	5.55	6.09	50	8.82	8.82
55	5.87	6.06	54	9.02	8.66
57	5.78	6.00			
60	5.42	5.93			

Station A is a medium-size plant of 30,000 kw. capacity. Station B is a small plant of 5500 kw. capacity. Both calculated costs are based upon the actual costs at a 50 per cent load factor. The choice of some other basis might have led to better closeness of fit of actual conditions and conditions assumed of formula, but would not have obviated the variations noted or spanned the maximum and minimum of the observed data.

An examination of the formula indicates why this is the case. The equation assumes a fixed relationship for all types of steam generation, makes no allowance for the operation of several units at different times or for the size of the equipment and its overload capacity. Assuming that the cost at 100 per cent load factor is unity, the formula fixes the cost at 20 per cent load factor at 1.47, a 50 per cent load factor at 1.19, a 60 per cent load factor at 1.14, etc. That important variations may be expected from the assumed standard is apparent from an inspection of the familiar economy curves of boilers, prime movers and generators. Various combinations of these factors are certain to effect changes in the resultant curve.

The cost sheet of the power plant at various load factors moreover, does not reflect merely the relation of input to output. It consists, especially in plants of limited capacity, of many items of cost fixed in their nature and independent of load factor or

output. Certain labor and maintenance items, for example may be expected to continue whether the plant is fully utilized or not. In small plants this constant quantity is of greater magnitude than in large plants and the effect on the cost at various loads is one of varying degree. All of these factors must be accounted for in any empirical formula designed to compare results of operation.

When the various items of power costs are separately scrutinized from month to month it is noted that each has its own basis of variation. Statistical units may be frequently developed to reduce these variables to more constant quantities and it is believed that this method of preserving data is the first step in the development of a cost formula. From a management standpoint increases in power costs are of particular interest because they are due partly to changes in the demand and load factor over which the management has little or no control and partly to direct additions to expense for which the responsibility can be directly localized. Both types of causes effect an increased cost per kilowatt-hour. The fuel cost which theoretically must be some function of the load factor will fall largely in the first class. The remaining items, labor, supplies, maintenance, etc., fall largely in the latter class and, while a small proportion of the total, is that part in which the greatest possibilities for economies in operation arise, and hence of the greatest interest.

A report form based upon a statistical comparison other than kilowatt-hour costs is used by one of the largest operating syndicates. The classification of accounts corresponds to that of the Public Service Commission of the state in which the plant is located. The data disclosed for the various items of steam and power plant costs are as follows:

STEAM GENERATION

No.	Account.	General Unit	Specific Unit
601	Boiler plant superintendence	sh. kw-hr.	Per cent. of 602-616
602	Boiler plant operating labor	"	Coal ton.
603	Coal and ash handling operating labor	"	Coal ton.
604	Water purification operating labor	"	100 cu.ft.
605	Fuel for steam (cost of fuel in storage)	"	Coal ton.
606	Water for steam	"	100 cu.ft.
607	Water purification supplies	"	100 cu.ft.
608	Boiler plant tools	"	Boiler h.p-hrs.
609	Boiler plant supplies and expenses	"	Boiler h.p-hrs.
610	Removal of ashes expense (haulage from plant)	"	Coal ton.
611	Maint. of boilers and boiler aux. equip. (labor)	"	Boiler h.p-hrs.
612	Maint. of boilers and boiler aux. equip. (sundries)	"	Boiler h.p-hrs.
613	Maint. of coal and ash handling equip. (labor)	"	Coal ton.
614	Maint. of coal and ash handling equip. (sundries)	"	Coal ton.
615	Maint. of water purification equip. (labor)	"	100 cu.ft.
616	Maint. of water purification equip. (sundries)	"	100 cu.ft.
617	Maint. of boiler plant bldgs., fix. and grounds (labor)	"	Boiler h.p-hrs.
618	Maint. boiler plant bldgs., fix. and grounds (sundries)	"	Boiler h.p-hrs.

ELECTRICAL GENERATION

No.	Account.	General Unit	Specific Unit
626	Prime mover plant superintendence	sb. kw-hr.	Per cent of 621-629. and 632-642.
627	Prime mover operating labor	"	kw. demand.
628	Prime mover plant elec. operating labor	"	kw. demand.
629	Prime mover plant macl. operating labor	"	kw. demand.
630	Steam generated (proportion of cost) accts. 601-618	"	kw. demand.
631	Steam purchased	"	kw. demand.
632	Prime mover plant lubricants	"	kw. demand.
633	Prime mover plant tools	"	kw. demand.
634	Prime mover plant supplies and expenses	"	kw. demand.
635	Maint. of prime mover (labor)	"	kw. demand.
636	Maint. of prime mover (sundries)	"	kw. demand.
637	Maint. of prime mover aux. equip. (labor)	"	kw. demand.
638	Maint. of prime mover aux. equip. (sundries)	"	kw. demand.
639	Maint. of generators and aux. gen. equip. (labor)	"	kw. demand.
640	Maint. of generators and aux. gen. equip. (sundries)	"	kw. demand.
641	Maint. of aux. electrical equip. (labor)	"	kw. demand.
642	Maint. of aux. electrical equip. (sundries)	"	kw. demand.
643	Maint. of prime mover plant bldgs., fix. and grounds (labor)	"	kw. demand.
644	Maint. of prime mover plant bldgs., fix. and grounds (sundries)	"	kw. demand.
731	Electric current exchanged (between plants)	"	kw. demand.

For large plants these costs are subdivided in greater detail although the units of comparison are similar. The statements are also supplemented by statistics of demand, capacity, output, coal, water and lubricants. It will be noted that the electric generation costs are classified under both the kilowatt or demand unit and the kilowatt-hour or output unit. Some of these items vary directly with the demand; others respond to changes in output. The large majority of items, however, vary with the load factor and are affected by both demand and output. Were the plant operated at 100 per cent load factor by far the greater portion of the "steam generation" expense then would be an output cost. While operated at less than 100 per cent load factor standby losses are developed, a large portion of which are eliminated with better load factors. Labor costs develop even greater standby losses at low load factors, and these items alone serve to explain why better economies are possible, than the formula presented would anticipate.

The varying items comprising station operating cost are of too great importance to be merged into a general formula even when expressed as an equation of the fourth power, if the purpose in comparison for the sake of determining relative efficiency or possible future economy. If it is possible to develop a single formula which reflects in like manner two types of operation, it is believed that a segregation of the following four items is essential:

(a) Operating costs continuing irrespective of the output, such as labor, maintenance, etc., but affected by the demand.

(b) Costs varying as some function of the load factor, such as fuel, labor, water, etc.

(c) Costs varying directly with the output.

(d) Overhead costs such as supervision.

Such a separation will not only provide the means for direct comparison of different plants but will give the separation of costs necessary to determine the charge to be borne by various services supplied by the same central station, such as traction and commercial lighting, and will serve as a basis for fixing the rate of charge to be made to customers under a demand and energy schedule. It also does not seem probable that fullest economy can be obtained in operation until those portions of cost which directly concern the management are separated from those costs which are dependent upon a varying public demand for service and hence without the control of the management.

S. D. Sprong (by letter): The following notes refer only to the paragraph entitled "Estimated Life of Apparatus", including Life Expectancy Table, of the paper by Messrs. H. G. Stott and W. S. Gorsuch.

I agree with the writer that estimating the life of apparatus is a highly speculative matter, but do not believe that all the figures given in the life expectancy table represent the results which have been obtained in first-class well designed power plants.

Between the years 1893 and 1898, a number of first-class steam-driven power plants were designed or erected in the greater city of New York. These plants were equipped with reciprocating engines, the majority of which are still in operation and apparently will continue to operate for years to come. It, therefore, seems that the total life of twelve years estimated for engines and condensers is far below what may actually be obtained in view of the number of engines now operating which are from 15 to 20 years of age. The same general statements apply to alternators for which the estimated life is stated as twelve years, as practically all the large alternators installed in New York City beginning with 1897, or sixteen years ago, are still in operation.

Synchronous converters are given an estimated life of twenty years. A number of these machines have been in operation in New York City from about the year 1894, and a large number of the batteries now in use have been in service from 10 to 15 years. The author estimates ten years as the average life of the battery, but there are a large number of batteries now operating in New York considerably older than this, and which batteries are still in first class condition. In the early days the battery manufacturers were willing to guarantee the total maintenance of the battery for 6 per cent of the cost which, without considering interest, would mean a life of over sixteen years. The actual scrap value of lead in batteries will run from 10 per cent to 20 per cent of the original cost, according to the condition of the

plates. The average life of a battery depends almost entirely upon its number of discharges rather than its life in years. The vehicle battery may have to be replaced yearly if discharged daily, whereas a station battery under average operating conditions would probably not have the same number of discharges in thirty years.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 26, 1913.

Copyright, 1913. By A. I. E. E.

AUTOMATIC SUBSTATIONS

BY H. R. SUMMERHAYES

The object of this paper is to describe the automatic substation at Detroit, in which there is working a synchronous converter controlled entirely from a distant station; some observations are made also on automatic substations in general.

While many motors of all sizes operate without attendance, and with little attention, practise has always required operators at converter substations. In earlier days the operators were necessary, but the converter is now such a reliable piece of apparatus that in some cases operators are not required, as in the station described in this paper.

Automatic Operation. Automatic operation, strictly defined, is that in which a machine performs its functions without any human control; in the Detroit station the control is from a distance but the apparatus may be said to be automatic, inasmuch as the various functions of starting, stopping and regulation are performed without the supervision of an attendant in the station where the machine is located.

The operation without an attendant of a commutating machine of fairly large size in a substation, supplying current to a commercial lighting system, is an idea so different from the generally accepted practise that to lead up to it some consideration will be given to more familiar examples of automatic substations.

Remote-controlled electrical apparatus is now widely used for a variety of different purposes. It is generally used for the reason that the machine to be controlled is so located as to be inaccessible, or for reasons of convenience, to save labor, or to concentrate at one point the control of a number of machines whose functions are related.

When the motor is inaccessible, either by reason of its location or being enclosed, or when it is out of sight and hearing of the operator, it does not matter whether the motor is in the next room or a mile away. It is only a question of degree.

The following are some of the more familiar examples of remote control. In some of these the machines which are operated by the electric control are visible to the operator and in other cases he receives signals, that the machine has operated, but in nearly all cases the electric motor is out of sight and receives only occasional attention and inspection.

Train Lighting. In systems of train lighting with an axle-driven generator, the generator itself is inaccessible and out of sight and receives only occasional attention. Its operation as to commutation, temperature rise, etc., is taken for granted and the control is usually by four automatic devices, *i.e.*,

1. A pole changer which reverses the polarity of the generator when the direction of motion of the car is reversed.

2. An automatic switch which keeps the generator disconnected from the system at low train speeds and connects it when a certain speed is reached.

3. A current regulator which varies the generator field so as to supply a constant current to the storage battery.

4. A lamp voltage regulator which operates usually by working on a variable resistance in the lamp circuit.

In the case of train lighting the generator is so inaccessible that it might as well be a mile away.

Transformer Substations. The transformer substation, whether out of doors or indoors, is one of the most familiar examples of operation of electrical apparatus without an attendant. Of course, the transformer is a piece of stationary apparatus, but even a transformer shares with moving machinery the possibility of injury by lightning or overload.

Regulators. It is not unusual practise for lighting companies supplying alternating current to install automatic feeder regulators in a transformer substation without an attendant and with only occasional inspection. Here we have a transformer with the addition of an intermittently moving machine. Small regulators are now built of the pole line type designed to be mounted outdoors on a pole and to operate continuously and automatically with very infrequent inspection. These regulators contain a continuously rotating motor.

Blower Motors and Pump Motors. These motors are frequently

located in inaccessible places and receive scant attention as to operation. They are started from a distance and are depended upon to give good commutation and to operate without undue heating or bearing trouble. They are frequently controlled by automatic pressure regulators or float switches, and may be located at a distance, so that the only indication the operator has of their having started is the current in his ammeter.

Transportation. A very large class of remote-controlled apparatus is used for various kinds of transportation, such as electric street railways, electric trains, elevators, cranes, ore-loading machinery, mine hoists, electric ship propulsion, etc. In all of these, the electric motor is remote from the operator and receives only periodical inspection. Its operation is taken for granted, but in most cases the operator sees the movement of the machinery driven and regulates the control accordingly. In case of large mine hoists, the hoist may be out of sight of the operator and he has merely an indicator showing its movements.

Lighting of Isolated Buildings. There are a good many installations for lighting of large residences, hotels, etc., in the country, consisting of a storage battery and generator and an internal combustion engine, which may be said to be examples of automatic substations, as in some of these installations arrangements are made so that the voltage of the storage battery is allowed to vary between narrow limits, the engine and generator being automatically started up at the lower limit and when the storage battery is charged to the higher limit the generator and engine are stopped. These installations do not require any attention so far as the generator is concerned, excepting the occasional inspection.

Further Applications. With these examples in mind in which electric motors, remotely controlled and operated practically without attendants, are used in sizes from a fraction of a horse power up to thousands of horse power, many of these motors being of the commutating type, and also considering the instances in which small commutating, direct-current generators are used, it is only a step further to apply the same principles to a generating station or a substation.

Induction Generator. It is planned to install on a hydroelectric system in the West, an induction generator of about 1400 kw. capacity located in a station, without an attendant, several miles from the main hydroelectric generating station of the same company. This machine, after being started up

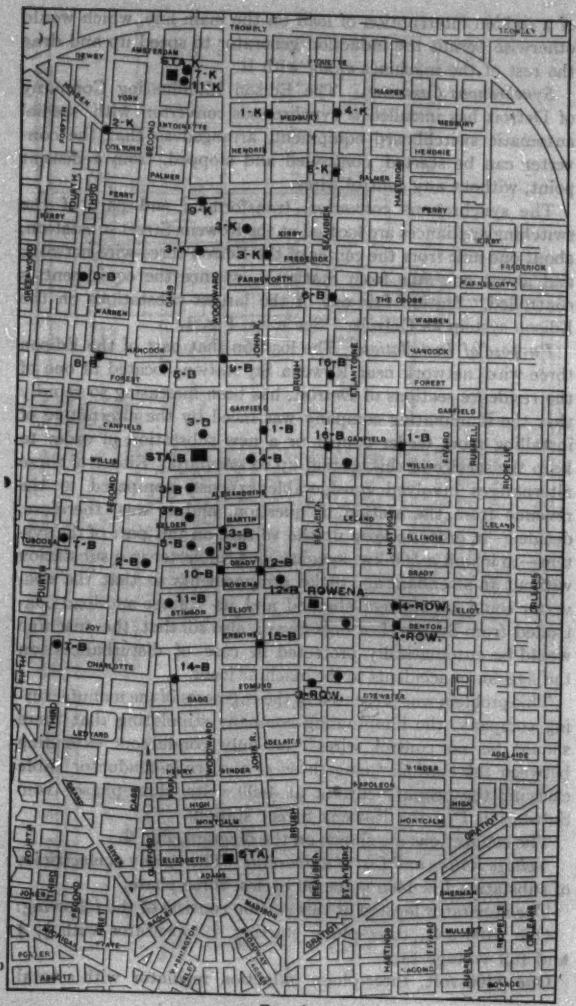
by an operator sent over for the purpose, will operate without any hydraulic governor, the waterwheel working at full gate all the time. While connected to the line, it will receive its magnetizing current from the synchronous generators in the other station and will deliver its full load into the system at all times when the load exceeds the rating of this induction generator. The frequency and speed will be controlled by the waterwheel governors at the main station in which most of the generators are of the larger capacity.

At times when the total load becomes less than the capacity of this machine, it will be disconnected by the operator at the main station opening the switch on the line leading to the induction generator. This generator will then run at nearly double speed and will be allowed to do so until again required, when an operator will be sent over to slow down the induction generator to a point approximating synchronism, when it may be thrown on the circuit again. It will, of course, be designed to run safely at double speed for any length of time, but in case of the machine not being required for a long period an operator would be sent over to shut it down.

It would be possible by the use of three or four control wires and a motor operated hydraulic governor to start up and shut down this machine from the main station, in which case the only attention required would be daily inspection and oiling of the hydraulic governor and such parts of the waterwheel as require oil. This installation is, of course, much simplified by not having any exciter. As at present planned, it is also much simplified by not having any hydraulic governor, so that the only moving parts in the station are the rotors of the waterwheel and generator which are on the same shaft and the only bearings are the thrust and steady bearings, which are lubricated by a simple oil pumping system in operation whenever the induction machine is running.

This induction generator, being rather slow speed and operating at 60 cycles, has a power factor of about 80 per cent. If the head permitted a high-speed generator, the power factor could be made much better.

It is worthy of note that this installation is on the same stream as the main plant but located above it, and will use the same water. The only governor will be an emergency over-speed trip which will not shut down the waterwheel but will simply disconnect the induction generator from the line in the event


TROMBLY
TOURTELLOTTE
HARPER
DEWEY
AMSTERDAM
STA. K
7-K
11-K
YORK
ANTOINETTE
1-K
MEDBURY
4-K
MEDBURY
2-K
COLUMBIA
HENDRIE
HENDRIE
PALMER
5-K
PALMER
PERRY
PERRY
KIRBY
9-K
2-K
KIRBY
KIRBY
3-K
FREDERICK
FREDERICK
FARNSWORTH
FARNSWORTH
6-B
8-B
THE GROVE
WARREN
WARREN
HANCOCK
HANCOCK
FOREST
5-B
9-B
10-B
FOREST
GARFIELD
GARFIELD
3-D
1-B
16-B
GARFIELD
1-B
WILLIS
STA. B
4-B
WILLIS
ALEXANDRINE
2-B
MARTIN
LELAND
LELAND
ILLINOIS
7-B
3-B
13-B
12-B
BRADY
BRADY
10-B
ROWENA
12-B
ROWENA
11-B
STIMSON
ELIOT
ELIOT
1-ROW
DENTON
1-ROW
JOY
15-B
ENSKINE
1-B
CHARLOTTE
14-B
EDMUND
3-ROW
STEWARTS
LEYLAND
ADELAIDE
ADELAIDE
HENRY
WINDER
WINDER
NAPOLEON
HIGH
HIGH
MONTCALM
MONTCALM
ELIZABETH
STA. A
ADAMS
SHERMAN
MULLETT
ACADIA
BOWDEN
ABBOTT
FORTIER
FORTIER
FORTIER

of a sudden interruption of load on the main line, which would otherwise permit the induction generator to speed up and drag the rest of the machines along with it.

Synchronous Converter. The Edison Illuminating Company of Detroit has installed a synchronous converter with special automatic switchboard equipment, arranged so that the converter can be started, controlled and stopped, from a distant point, without any control wires.

The synchronous converter, transformers and part of the switching appliances are located at the Rowena Street substation, about one mile from the center of the Edison three-wire network and about one mile from Station I, whence the equipment is controlled. Station I is one of the largest substations on the Edison system at Detroit. See map, Fig. 1.

Purpose of Installation. The load on that part of the Edison three-wire network near Rowena St. station, located in one of the residence sections of Detroit, has been increasing so rapidly that the illuminating company was faced by the alternative of installing more feeder copper or a new substation in order to keep the service in this section up to standard. Either of these alternatives involved considerable expense, compared to the revenue from the section in question, and it was, therefore, decided—in order to keep up the voltage on this part of the system—to install a 500-kw. synchronous converter in a substation without an attendant and make arrangements so that the converter could be started, stopped and its voltage and load controlled from Station I a mile away; also so that the machine would be automatically protected in case of disturbances on the system or accidents to the machine itself.

This problem was presented to the engineers of the manufacturing company, the illuminating company stipulating that there should be no control wires, the only conductors extending between the stations being those of the triple-conductor cable carrying the primary current at 4400 volts, three-phase, from Substation I to the Rowena Street station.

The connections are shown on the diagram, Fig. 2.

Voltage Rating and List of Apparatus. The supply of electricity of substation I is 4400 volts, 60 cycles, three-phase.

The apparatus located at this station consists of the following:

One 4400-volt, three-phase starting compensator with $\frac{1}{2}$, $\frac{3}{4}$ and full voltage taps.

One 4400-volt, three-phase induction regulator with a total

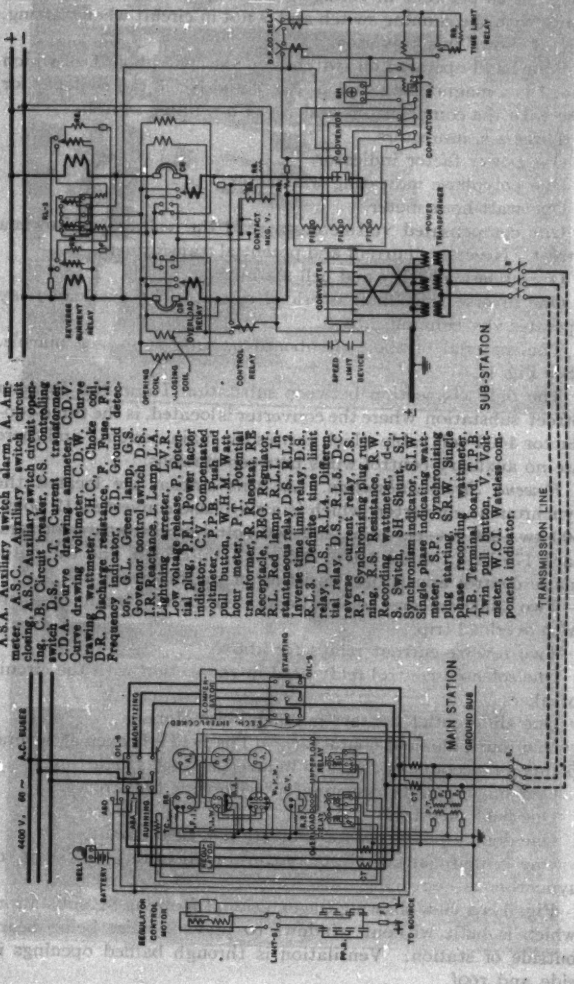


FIG. 2—DIAGRAM OF CONNECTIONS

range of 20 per cent in voltage. The regulator is connected in series with the running switch and is not in circuit when starting. Fig. 3 shows this regulator.

Four hand-operated oil switches on the switchboard, of which No. 1 is a magnetizing switch, No. 2 and No. 3 tap switches for use with the compensator, and No. 4 a running switch.

Three a-c. ammeters.

One power factor indicator.

One polyphase indicating wattmeter.

One watt-hour meter.

One compensated voltmeter to read the voltage at Rowena Street. Necessary current and potential transformers.

One underload relay and bell alarm.

One inverse time limit overload relay. The overload relay operates the running switch.

The material of the switchboard is pink Tennessee marble. (See Fig. 4).

The only connection between substation I and the Rowena Street substation where the converter is located, is the three-conductor 4400-volt cable which carries the main current, and there are no auxiliary control wires between stations.

Rowena Street Substation. At this station are located the synchronous converter, which is a six-phase converter, 12 poles, 500 kw., 600 rev. per min., 250–300 volt d-c., three transformers, each 175 kv-a., rated 4400—205 volts, oil-cooled, and the automatic control apparatus consisting of the following:

Two 3000-ampere solenoid-operated main circuit breakers with overload trip.

Two reverse-current relays for above.

One solenoid-control relay used in connection with the circuit breakers.

One differential contact-making voltmeter.

One four-pole field contactor. (The field is broken at several points, on account of the high induced voltage at starting.)

One single-pole field contactor, with time limit relay.

One field rheostat.

One double-pole relay for protection of field circuit.

One centrifugal switch or governor mounted on shaft of synchronous converter.

Fig. 5 is a view showing the exterior of Rowena St. substation, which is built without windows to prevent noise being heard outside of station. Ventilation is through baffled openings in side and roof.

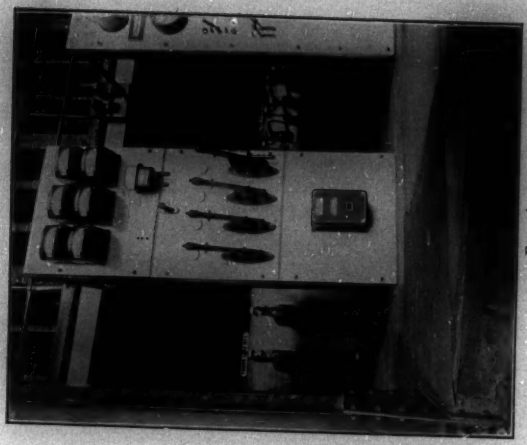


FIG. 4 [SUMMERHAYES]

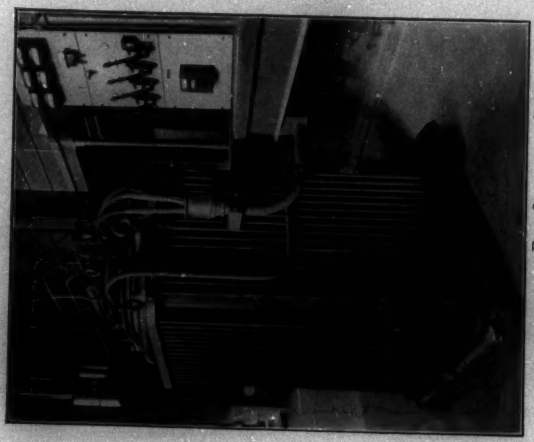


FIG. 3 [SUMMERHAYES]

FIG. 5 [SUMMERHAYES]

FIG. 6 [SUMMERHAYES]

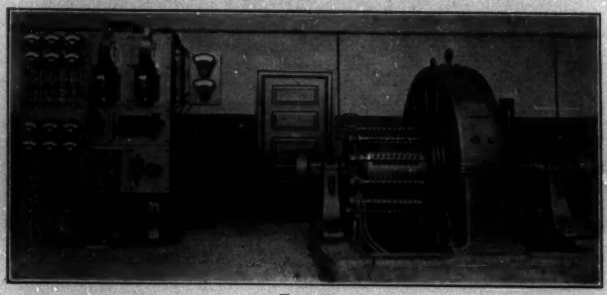


FIG. 7 [SUMMERHAYES]

FIG. 8 [SUMMERHAYES]

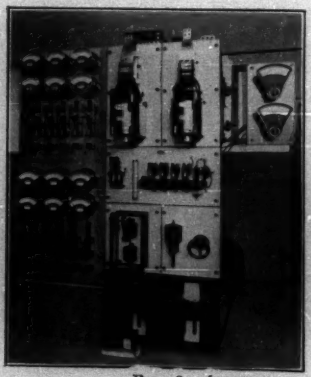


FIG. 9 [SUMMERHAYES]

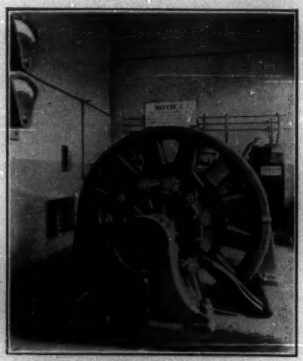


FIG. 10 [SUMMERHAYES]

Fig. 6 is a general view of the interior, Fig. 7 shows the converter and switchboard, and Fig. 8 shows the transformers, also the end of the converter shaft with speed limit switch.

Fig. 9 is a front view of switchboard showing the automatic control device at right and feeder panel at the left, and Fig. 10 is an end view of the converter showing the centrifugal governor or field switch.

All of the devices of the control equipment, excepting the field rheostat and governor, are mounted on two pink Tennessee marble panels.

The circuit breakers are supplied with sockets and auxiliary handle so that they may be worked by hand.

A number of feeders connected to different points on the 125–250-volt Edison three-wire system in this vicinity are brought into the Rowena Street substation and the feeder switches are normally left closed so that there is 250 volts on the bus in this station available to operate the contactors which close the field when the control circuit of these contactors is closed by the governor.

Operation

Starting. In order to start up the converter, the operator at substation I proceeds as follows:

First: The induction regulator is set at maximum lowering position.

Second: The magnetizing switch is closed.

Third: The $\frac{1}{3}$ tap switch is closed, throwing $\frac{1}{3}$ voltage on the line leading to the Rowena Street substation. The converter starts on this tap and reaches synchronism in 20 or 30 seconds. Just before the converter reaches synchronism (that is, within 5 per cent of synchronism), the governor on its shaft closes the control circuit of the field contactors and the four-pole contactor operates immediately, exciting the rotary converter field from the bus so as to give it the correct polarity, but with a considerable resistance in series with the field. As soon as this weak field is thrown on, the rotary converter pulls into synchronism with the proper polarity but at $\frac{1}{3}$ voltage. This operation is made evident to the operator at I street by watching his a-c. ammeter, on which the current decreases from the initial starting current to about $\frac{1}{3}$, and suddenly increases as the field is automatically applied, then settles to a low and steady value as the converter falls into synchronism.

Fourth: Just after the automatic application of the field, the operator opens the $\frac{1}{3}$ tap switch and closes the $\frac{2}{3}$ tap switch.

Fifth: The operator then opens the $\frac{3}{4}$ tap switch and closes the running switch. After the closing of this switch the converter is in synchronism but operating at a low d-c. voltage on account of the position of the induction regulator and operating with a very weak field. On account of the weak field, the power factor at this time will be lagging.

Sixth: Within a few seconds the second field contactor automatically operates, cutting out sufficient field rheostat so as to give the rotary full normal field current. The control circuit of this contactor was closed by the governor at the same time as the other contactor, but its operation was delayed by a time limit relay. The operation of this contactor is immediately evident to the operator at Station I by the increase in current on the a-c. ammeter and the changing of the power factor from lagging to leading.

Seventh: At this point the converter is running in synchronism with full field and correct polarity and all ready to be connected to the direct-current buses, excepting that its voltage is low, owing to the position of the induction regulator. The operator now brings up the voltage by the induction regulator and at the moment the voltage across the brushes of the converter exceeds by a very small percentage the voltage on the buses, the contact making voltmeter operates. This device is differentially wound, one coil connected to the buses and the other to the brushes of the converter. The bus voltage may vary at different times of day from 250 to 300 but whatever voltage is across the buses, this differential device acts only when the synchronous converter voltage exceeds the bus voltage by a small percentage. This device makes a circuit through the control relay which operates the closing coils of the two main circuit breakers and connects the synchronous converter to the busbars. This action is so accurate that the converter may be made to take any percentage of load that is required. Ordinarily it is so adjusted that when the circuit breakers close, the converter takes about one-tenth load.

Load Control, Etc. The voltage at points on the Edison three-wire system in the neighborhood of the Rowena Street station is observed at Station I by means of the pressure wires ordinarily used on these Edison systems and the amount of load taken by the converter at Rowena Street is changed by the operator to meet the voltage conditions on the system. The change in load is effected by manipulating the induction regulator.

The amount of load at any time is indicated by the a-c.

ammeters in connection with the indicating wattmeter and the power factor meter.

Stopping. In order to stop the synchronous converter, the running switch at Substation I is opened. This disconnects the a-c. supply and leaves the synchronous converter running as a d-c. motor. The reverse-current relays are set so that they will operate on the current which the converter takes as a d-c. motor and their operation opens the main circuit breakers and disconnects the converter from the d-c. busbars and, as the converter slows down, the governor resumes its starting position and the field contactors open so that everything is ready for a new start.

Protection. In case of a short circuit on the a-c. system at some point between the main station and the switchboard at Station I, the d-c. current feeding back from the d-c. systems through the synchronous converter operates the reverse-current relays and opens the solenoid circuit breakers so that the converter is left connected to the a-c. system. When the a-c. short circuit disappears and the a-c. voltage comes up again to normal the converter is automatically connected in the d-c. system again, unless the current required to synchronize the converter is heavy enough to open the main switch at Station I by means of the overload relay, in which case the converter may be synchronized by the magnetizing and tap switches, as explained under "Starting."

In case of a short circuit on the a-c. circuit or on the cable between Station I and Rowena Street, or in the armature, transformers or regulator, the direct current feeding through the converter into the short circuit operates the reverse-current relays and opens the solenoid circuit breakers, and the alternating current feeding into the short circuit operates the overload relay and opens the main switch at Station I, disconnecting the converter from the line. With the original equipment, time limit attachments were added to the reverse-current relays so that they would not operate in case of mere momentary surges. These relays are not being used in the actual operation of the equipment as they are considered unnecessary by the illuminating company. Two reverse-current relays are used so that safety is assured. If both should fail, the speed-limiting device and the overload coil are both available to open the d-c. circuit breakers.

In case of a short circuit on the d-c. side, the overload relay at Station I will open the running switch and the converter will

be disconnected as in the ordinary operation of shutting down. If this d-c. short circuit is a very severe one, the overload trip coils of the circuit breakers which are set rather high will also operate.

The field circuit of the synchronous converter is protected by means of a double-pole overload relay. The shut-down of the converter from any cause is indicated by the underload relay at Substation I.

This station has been operated ever since it started without any regular attendant, but since the equipment was novel, for the first few weeks it was the practise to send a man over from Substation I to watch the operation when the outfit was being started and in this way several points have been observed which have enabled us to perfect the equipment.

The centrifugal switch originally used to close the field circuit was found to be unsuitable, and this has been replaced by one of different design, which is reliable and has given satisfaction. During the few days the first switch was out of service, the field contactor circuit was closed by hand when the machine was being started. Shortly after installation there were two or three cases when the machine failed to start; such failures have now been eliminated by proper adjustment and minor changes in the relays. It is the intention to have this equipment inspected once a day.

The illuminating company may decide later to put in a thermostat on the bearings, recording through a telephone wire to Substation I, so as to eliminate danger from this source, but it is not believed this will be necessary.

The bearings are of the ring oiling type generally used on machines of this class, so that very little trouble may be expected.

In addition to the governor used for closing the field circuit, the synchronous converter is equipped with the usual centrifugal speed limit device.

The illuminating company expects to extend this remote control system to other substations.

Fire Risk. The fire risk is practically nil, except for the chance of the windings of the machine taking fire from an accidental burn-out. This may be minimized by automatic extinguishers. It would not be possible to use automatic sprinklers in a cold climate unless the substations were heated, but some automatic extinguisher, using Pyrene or similar liquid freezing at a lower temperature, may be devised, and this would be preferable to water for other reasons as well.

Other Applications. In the station described, the converter is of the type without commutating poles. An automatic installation including a commutating-pole converter, would require a solenoid mechanism for raising the brushes when the field contactors open while the machine is shutting down, the same mechanism to lower the brushes when the machine has started and reached synchronism. This would be worked by the closing of the field contactors.

When an automatic substation is installed on an Edison system the field contactors may be operated from the 250-volt bus, connected to the system outside, and it may be assumed there is always voltage on this system.

In case of an automatic substation on an electric railway system, it may be desired to start up the station when there is no voltage on the trolley wire. In such a case the machine may come up to speed with the wrong polarity, since there is no means of determining the polarity by exciting the field from the trolley. To meet this requirement, a special relay, devised by Mr. J. B. Taylor, or a storage battery, may be used. Since railway substations are generally located on the line of the railway, it is frequently found convenient to combine the substation with a waiting room and ticket office, so that the operator performs both functions. Where it is not necessary to do this the automatic substation may be used.

Still another application of these principles may be to simplify the control of machines in a large station containing several converters. That is to say, the low-tension switches near the machine will be eliminated and one operator at the switchboard would take care of the entire starting.

While the automatic starting of this converter as described in detail may seem complicated, in actual practise it is very simple, as it merely requires the operator to close four oil switches in rotation, 1, 2, 3, 4, and to manipulate an induction regulator, the machine being thrown on the system with very little disturbance.

Conclusion. The remote control of synchronous converters enables a plant operating the Edison three-wire system to extend the economical limits of the system, since the cost of the labor of station operators and the cost of heating the building forms a large proportion of the running expense of a substation. With the station heating expense and the regular watch of station operators eliminated and the labor expense limited to

the cost of daily inspection, it becomes possible to operate substations where previously the density of the load would not warrant a substation.

In general, this means that the Edison three-wire system in a city may economically be extended to cover a greater territory than at present. It will be possible to reduce the investment in feeder copper by using smaller substations set closer together.

Acknowledgment is made to Mr. G. W. Cato, of the Edison Illuminating Company of Detroit, for information and illustrations used in this paper.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 26, 1913.

Copyright, 1913. By A. I. E. E.

CONVERTING SUBSTATIONS IN BASEMENTS AND SUB-BASEMENTS

BY B. G. JAMIESON

The type of substation discussed in this paper is that which is located below street grade in commercial buildings of large cities. Sub-grade at once suggests valuable real estate, crowded quarters flooded basements, ventilating difficulties and machinery handling problems. Coupled with these disadvantages and risks are certain economies and other features which have made these substations a matter of much importance in our largest cities. The purpose of this paper is to show the influence of these factors upon the apparatus and arrangement of this type of substation.

In the down-town district of Chicago, for example, the development of converting substations below street level has covered a period of approximately fifteen years and in that time the capacity of single converting units has increased from 250 kw. to 3500 kw., and fortunately the building art has so advanced that head-room of from 15 to 26 ft. (4.5 to 7.9 m.) has been made available in some of the sites more recently secured. In the heart of Chicago, practically within the "loop," there are ten substations either in service or about to be commissioned which have a combined capacity of 42,000 kw. in converting apparatus or storage batteries, all operating on the Edison three-wire system, eight of which, with a total capacity of 29,000 kw., are of this sub-grade type. One of the latest substations has an ultimate capacity of four 3500-kw. and one 2000-kw. synchronous converters; one of the earliest has eight 500-kw. and four 1000-kw. converters. The district has an area of only 0.81 sq. mi. (2.1 sq. km.) and a connected load of 1,940,000 lamps (50-watt equivalent), a maximum last year of 31,000 kw. and an annual

load factor of 32 per cent. Fig. 1 shows the 24-hour load on the day of maximum kw. in the winter of 1912, and Table I shows the annual kw. increment, an interesting table, in which may be discerned indiscriminate periods of great business expansion and depression and, faintly, the advent of the tungsten lamp.

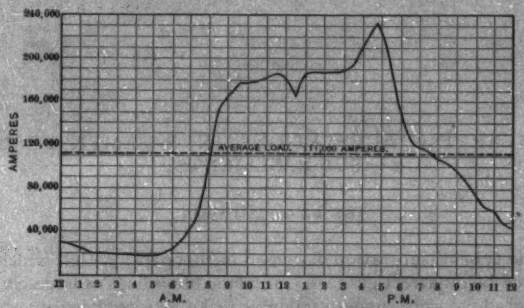


FIG. 1—LOW-TENSION DOWN-TOWN DIRECT-CURRENT LOAD ON DAY OF MAXIMUM OUTPUT—DEC. 16, 1912

Devoid of all exterior attractiveness, these converting substations may be viewed from the engineer's standpoint as a series of large, deep pits surrounded by concrete walls, upon which devolves the duty of resisting the inward thrust of the

TABLE I

PER CENT OF INCREASE OF DOWN-TOWN LOW-TENSION MAXIMUM LOAD

	Per cent
1901 over 1900	15.5 increase.
1902 " 1901	25.7 "
1903 " 1902	18.5 "
1904 " 1903	5.5 "
1905 " 1904	27.4 "
1906 " 1905	5.4 "
1907 " 1906	7.8 "
1908 " 1907	3.0 "
1909 " 1908	10.0 "
1910 " 1909	1.7 decrease
1911 " 1910	6.4 increase
1912 " 1911	4.8 "
1913 " 1912	7.0 increase (estimated)

abutting earth and of keeping out the surface and sub-soil water, bottomed with a layer of concrete which must be heavy enough to keep the earth from crowding up into the pit, and intersected vertically by numerous columns which keep

thousands of tons of steel, concrete, and tile from falling into it. Occasionally a group of fire engines may pour or a broken street main may liberate perhaps 10,000 gal. (37,854 l.) of water per minute directly over the roof of the pit, which has two open stair wells, a shaft of approximately 175 sq. ft. (16.2 sq. m.) to admit apparatus, and air ducts of 50 sq. ft. (4.6 sq. m.) section; and with all this the converters must operate continuously. Quite different from the super-grade structure, the comparatively simple duty of which is to protect the apparatus from the weather.

The sub-grade substations may be grouped in two classes, I—the basement type, and II—the sub-basement type, the distinguishing feature being that Class I usually includes the sub-sidewalk space and may be reached directly from the street or sidewalk level; whereas Class II may be either a first or second

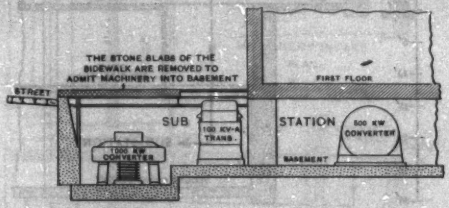


FIG. 2—SECTIONAL ELEVATION, BASEMENT TYPE

sub-basement of a twenty-story building, which is isolated from both street and sidewalk. Figs. 2 and 3 show the conventional forms of entrances to these two types.

Class I typifies the earlier stage of the development when basement space was not so valuable as now and in many ways presented proportionately as great construction problems as Class II, for, even though the depth was not so great, the adaptation of a given space for an electrical substation had to be carried out at the foundations of a high building designed without thought of such purpose.

In contrast to the ordinary super-grade substation there is no convenient 12- or 14-ft. (3.6- or 4.3-m.) doorway, with a crane just inside for admitting and handling a 7000-lb. (3175-kg.) transformer. The roof of the substation is on the level of the sidewalk and the space above the roof is another's premises. Access must be had through the sidewalk or adjacent alley.

The Class I machinery entrances are usually simply sidewalk slabs, the removal of which gives a clear opening into the substation, while Class II intakes may be expensive shafts with offsets, totaling 40 ft. (12.2 m.) in depth. Fig. 6 shows the method of lowering a 3850-kv-a. transformer through a Class II entrance. Work of this sort is exceedingly precarious and requires the utmost caution on the part of the engineer in charge, for the shifting of centers of gravity with respect to points of support, and of the points of maximum bearing pressure, are made rapidly and in a manner often not contemplated in the

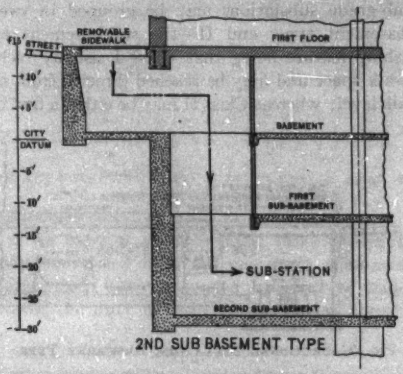


FIG. 3 —SECTIONAL ELEVATION, SECOND SUB-BASEMENT TYPE

design of apparatus. Clearances of an inch (25.4 mm.) or less are common in this class of work.

In the utilization of this entrance many untoward factors materialize. In a crowded business street only a limited time is allowed at the week-end, seldom exceeding thirty consecutive hours, in which sidewalk slabs must be removed, the machinery put in the substation space and the sidewalk slabs put back into original position. This usually means night and Sunday work to be carried out regardless of weather conditions. The effect of this close work may be reflected as far back as the factory from which shipment of apparatus is made. To illustrate—a 3500-kw. synchronous converter with its appurtenances, a gross weight of 135 tons, must be brought into the substation on a certain

date. Factory shipment is scheduled accordingly, allowing for the vicissitudes of railway transportation, so that demurrage may be avoided. The apparatus must be especially cribbed to fit the entrance to substation, or perhaps only partially assembled or so arranged on the cars that proper order of removal may be followed; perhaps a particular 15-ton piece has to be placed on the wagon in a certain manner because it is not possible to reverse its position after loading.

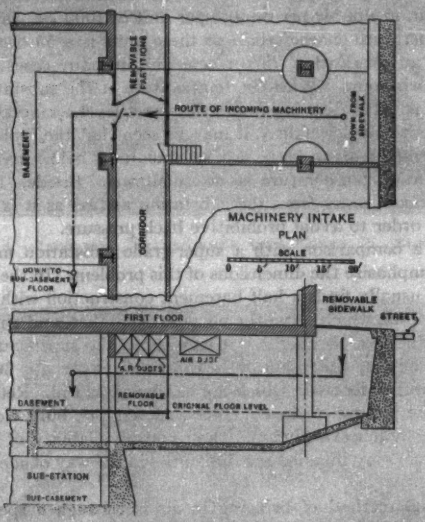


FIG. 6—PLAN AND SECTIONAL ELEVATION OF MACHINERY INTAKE

In the Class I substations, there is naturally more latitude in the choice of location for this entrance than in Class II, and consequently the work is generally less difficult. The parts to be handled are usually smaller in Class I substations, so that Class II machinery handling problems are much more serious. For instance, one substation has a machinery intake in the exact form shown in Fig. 3, the course of incoming machinery being indicated by dotted line. The apparatus may be 10-ft. (3.05-m.) cubic elements weighing 25 tons, and cribbed for two or three

inches (50 to 75 mm.) clearance. The shaft walls are lightly supported, so all weight must be taken from lowest floor. Fig. 5 shows the section of a machinery entrance and passageway in another substation under construction, which had to be practically hewn out of a finished building basement. Fig. 6 shows a diagram of this same entrance.

Of really greater importance to these substations is the matter of air supply, because until recently all synchronous converters installed on the Chicago system had air-blast transformers and regulators and required under extreme conditions 10,000 cu. ft. (283 cu. m.) of air per minute per unit of 1000 kw. capacity. The temperature characteristic of these units is a 55 deg. cent. rise with an overload of 25 per cent and in many cases 50 per cent for two hours. With the temperature of the substation at 40 deg. cent. (104 deg. fahr.) and the street level temperature at 35 deg. cent. (95 deg. fahr.), it may be seen that the problem of bringing enough air to keep, say, six such units below maximum safe insulation temperature is no small one. Besides, the air must be taken away from the substation as fast as it is introduced, in order to avoid prohibitive back pressure.

Again, a comparison with a super-grade substation may be made to emphasize the dimensions of this problem. In the latter type, one usually finds a half basement construction with numerous windows, which serve the purpose of intakes, and an array of large windows, also perhaps a monitor in the superstructure, readily permitting the escape of the heated air,or perhaps 300 sq. ft. (28 sq. m.) of doorway which can be opened at will. Referring back to the picture of the concrete enclosed pit, built close to the lot lines, and bearing in mind the usual inviolability of building lines, one may imagine the difficulties in the way of adequate air supply.

The usual method of bringing in air is through a specially designed grating in the sidewalk, which must be so located that it will not inconvenience the public or the tenant whose business is carried on just above the substation. The street level location of the air intake gives rise to one of the most serious faults characteristic of air supply systems of this sort, viz., the unavoidable entrainment of large quantities of dirt. Grating, screens, and washing devices are of but little avail against the volumes of dirt swept along with the 40,000 or 50,000 cu. ft. (1130–1410 cu. m.) of air per minute which scours the street on its way to the intake.

[JAMIESON]

FIG. 4.—LOWERING TRANSFORMER INTO COURT PL. SUBSTATION

[JAMIESON]

FIG. 5.—MACHINERY INTAKE, SHERMAN STREET SUBSTATION

FIG. 7.—VACUUM-CLEANED AIR SCREEN, HARRISON STREET SUBSTATION [JAMIESON]

FIG. 8 [JAMIESON]

FIG. 9 [JAMIESON]

FIG. 10 [JAMIESON]

Again, during freezing weather, ice and snow make trouble and in some cases require special construction for their control. The dirt is, however, the most serious drawback. It can be removed from the exterior of accessible surfaces more or less easily, but when blown into the air ducts of an internally cooled transformer or regulator for a period of years, the weekly cleaning of apparatus retards but slightly the inevitable clogging of these passages. Manufacturers have been slow to recognize these conditions as unavoidable, but lately have offered some aid by the provision of internal ducts of less tortuousness, which may be more effectively cleaned.

The principal objections to air-cleaning chambers and devices have been first cost, space required, resistance to passage of air and operating expense. One promising new device is a screen, differing from ordinary screens, in that it is self-cleaning. That is, a motor-driven endless cloth screen travels past a fixed vacuum sweeper, and all dirt deposited can be removed as fast as desired by simply varying the rate of travel of the screen. This screen under test caused a surprisingly low drop of pressure, considering the thickness of cloth. Fig. 7 shows a partial view of this machine, viewed from the substation side.

Cooling air is drawn through the screening device, usually by blowers in duplicate and of the curved vane type, each usually having a capacity of 25,000 cu. ft. (708 cu. m.) per minute at 1¼ oz. (35.5 g.) pressure, and impelled through sub-floor ducts to the converting unit.

As constructed, air-blast synchronous converter outfits are not entirely adapted for service in these sub-grade substations. In the super-grade substations where multitudinous windows and large doors are possible, little attention is necessary to the disposal of the heated air, as the numerous exits tend to diffuse the air currents. In the sub-grade type, however, the direction that all air currents take upon leaving the room is generally towards a given point and this fact makes the cooling of adjacent converters very difficult. A synchronous converter is usually constructed as though it were intended to operate where cool air can impinge from all directions. When operating in an enclosed substation in close proximity to adjacent units where blasts of heated air are being thrown out by the complex fan action of their revolving armatures and drawn toward one corner of the room by the exhaust fan, they are subject to dangerous overheating. The transformers and regulators do not suffer

as much, proportionately, because of the structurally directed internal air blast. The obvious remedy is to treat the exhaust air as we treat the supply air, and lead it away through ducts, which is fairly easy in the case of the transformer. But to do this effectively with the synchronous converter is much more difficult. Radial, shaftwise, and eddy currents are so indiscriminate that the problem of corralling them and leading them off in ducts is very difficult without sacrificing accessibility of the working parts of the converter.

Figs. 8, 9 and 10 show some installations of this sort of exhaust duct system, which actually lowered the temperature of a 5000-kw. substation 11 deg. cent. (20 deg. fahr.).

The exhaust fan is usually a single unit of the positive blower type, in some cases of a capacity of 25,000 cu. ft. (708 cu. m.) per minute at 1½ oz. (42.5 g.). Disk fans are inadequate, because of the resistance of available exhaust passages.

After the air has performed its cooling functions it must be disposed of at its intake rate of perhaps 60,000 cu. ft. (1700 cu. m.) per minute. It cannot be returned through the sidewalk, for such a blast would be a public nuisance, so advantage is taken of every available uptake towards the roof—the building stack or its shaft, any available ventilating or conduit shaft, or perhaps a separate duct, erected against the exterior wall in the light court.

For the service from battery rooms the exhaust blower and shaft must be impervious to acid fumes, which means special construction in each case. Bronze fans or lead-lined stacks were the standards of earlier practise, but owing to cost and difficulty with lead linings in stacks of considerable height, experience is being sought with plastered ducts. In one case a steel impeller with acid-proof paint seems to have met the requirements amply.

The difficulties experienced with the air-blast type synchronous converter outfits finally forced attention towards water-cooled units, the expense of water supply having long delayed consideration of this type. Three substations are in course of erection in Chicago which will utilize converter outfits cooled by water from the city mains. These units are of 2000 and 3500 kw. capacity. Air will still be required for revolving apparatus, but with the increase in capacity and the consequent reduction in number of units per substation, the problem of adequate housing and duct work to facilitate cooling is simplified.

The city water has an average yearly temperature of 10 deg.

cent. (51 deg. fahr.) and a summer temperature of 22 deg. cent. (72 deg. fahr.), which is much lower than available cooling air previously referred to. As the 3850-kv-a. transformer requires 24 gal. (90.8 l.) of water per minute at full load with a load factor of 32 per cent, the theoretical substation requirements average 2900 gal. (10,980 l.) per 1000 kw. per 24 hours. The calculation assumes the operation of units in a group of substations in exact conformity with the load curve in the district. The actual consumption will, of course, be in excess of this amount because of the manifest impossibility of accomplishing this without underloads. But since the periods of full load occur during the winter and we are dealing with absolute temperatures, overloads may be taken with less than proportionate increase in the gallons per minute consumption.

The theoretical temperature rise of this discharge water from a 3850-kv-a. transformer at full load is approximately 10 deg. cent. (18 deg. fahr.), which checks fairly well with results gained from operation of similar apparatus. This warm water, it is intended, will be wholly or partly sold to the building management, whose requirements may reach 50,000 gal. (189,270 l.) per day.

As the substations are developed and the amount of waste water attains economical significance some reclaiming or recirculating system will undoubtedly be adopted, but operating experience will afford the best guide to a selection of the proper system.

Fig. 11 shows the connections of the water and oil piping system. Attention is called to the fact that this is an open system, the street main pressure being depended upon to force water through the cooling coils and the discharge being open to atmosphere. All apparatus is, however, below the level of the street mains and sewer. Ejector pumps in duplicate are used to lift the water to the sewer from the discharge tank or to the building mains. Duplicate supply services from mains to different streets, duplicate ejector pumps and the general reliability of the water supply of a large city, all make for the security which must be a feature in a system of this kind.

In each of the 3850-kv-a. transformers there are 3100 gal. (11,730 l.) of oil which must be capable of being easily introduced, renovated, and replaced. The transformers are enclosed by compartments of concrete with doors of iron, which are practically tight. An open drain of 324 sq. in. (2090 sq. cm.) runs

beneath the several compartments and is intended to convey to a 3500-gal. (13,250-l.) pump, any oil which might be suddenly liberated from the transformer casing. A considerable piping system is needed for accomplishing this. Preliminary to the design of the oil piping system opinions were asked of engineers and manufacturers, regarding the necessity of providing for quick discharge of the oil in emergencies. Operating engineers favored this provision, but the manufacturers claimed that it is sufficient to close the transformer tightly in case of fire in order to retain the oil, and smother any flames which might occur.

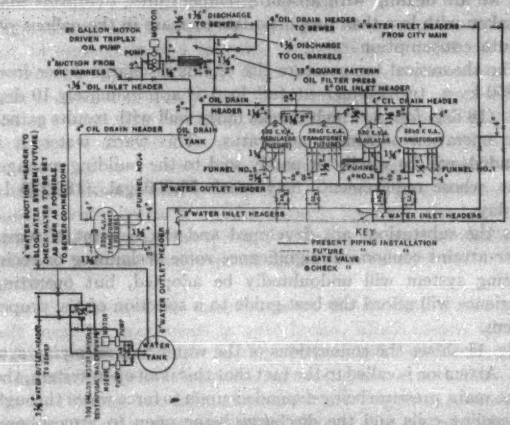


FIG. 11—DIAGRAM OF CONNECTIONS FOR OIL AND WATER PIPING FOR TRANSFORMERS AND REGULATORS

It is, of course, desirable to retain the oil in case of fire as this would undoubtedly lessen the damage to the transformer, but the oil may be liberated by an arc burning a hole through the case, in which event it may be very valuable to have means for quickly drawing off the oil.

In the diagram, Fig. 11, are several special features designed to increase the universality of the oil pipe system as much as possible, and the construction is such as to amplify in every possible way all precautionary features. The pumps, which are shown as a part of the oil filter system, are so connected that they

may serve either as filter or ejector pumps. Also the large sump shown, which is beneath the floor, may act either as a temporary storage of renovated oil or as a receiver for oil lost from a unit in service.

The reason for the apparently high structural cost of these sub-grade substations is the dual relation of the construction to the building itself and to the apparatus installed. It is expensive to construct deep walls actually proof against water leaking and to provide for locating machinery upon a floor, which serves also the purpose of holding the building together, because essential features of such a type of floor construction will generally limit its adaptation to other purposes. For instance, just at the point where cable space is needed behind a switchboard a false wall may require an extra foot (30 cm.), or just at the point where air ducts may be desired in the floor, a 36-in. (91-cm.) steel girder or its concrete equivalent may be located; or, as in one recent site, the whole floor must be reinforced so as to keep the earth below the building from being thrust upwards.

In one of the older substations where spread footing of columns claimed nearly 50 per cent of the available loading area of the basement floor, about one-half the weight of the battery, or 400 tons, had as a consequence to be carried on cantilever beams under the floor.

If the building in which the substation is to be located is an old one and only small units are to be installed, then the cost of the building construction required may be fairly low per unit but the cost per kilowatt high. If the building is an old one and the apparatus to be installed is of a size of the more modern units, then the cost of building construction per unit may be doubled, but the cost per kilowatt will be lower. If the building be a new structure and plans for substations can be made a part of building plans proper, the substation structural cost will be reduced very materially.

Building ordinances and other municipal regulations and interests play a considerable part in the development of these sites, and, together with the extraordinary nature of the business of the substation as compared with that of the average tenant of large down-town buildings, bring about some anomalous conditions. Ventilation, sidewalk restrictions, emergency exits, street and alley compensation and other matters not so prominent in ordinary construction, feature strongly.

It seems quite pertinent to emphasize a fact that has a bearing

on appraisals of this portion of an operating company's invested capital in rented properties. There is probably no portion of the company's real property where large sums of money may be invested for structural purposes with so little visible result as in the construction of a system of these substations. Conduit systems are more invisible, but a simple street chart and a few unit costs afford a very accurate guide to estimating of values.

The type of apparatus installed in these substations fixes the interior construction to a great extent. Synchronous converters are here practically the only type of units in use. Gross floor spaces of 0.95 sq. ft. (0.088 sq. m.) per kw. were average figures

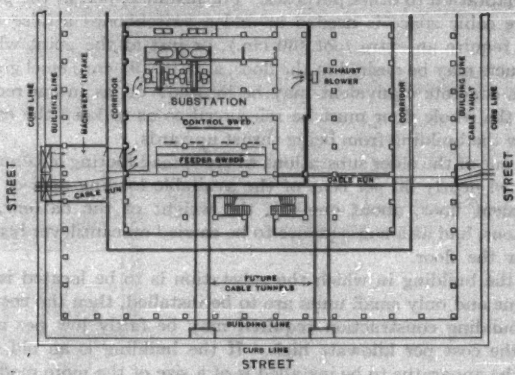


FIG. 12

for substations containing units up to 500 kw. capacity, whereas 0.54 sq. ft. (0.05 sq. m.) per kw. suffices for substations containing 3500-kw. units. Remembering that the transmission and distribution apparatus do not require any less space per kilowatt than they did with smaller units, it is clear that the large units have contributed wonderfully towards economy of space.

Figs. 12 and 13 show a plan and elevation of one of the largest and most modern substations of the sub-grade type which is under construction. This substation has 26 ft. (7.9 m.) head room, and floor space, including gallery, of 10,600 sq. ft. (985 sq. m.), which will permit of 16,000 kw. in converter capacity and a battery capacity of 1875 kw. (one-hour rate). One con-

spicuous feature is the ease of access to the conduit system in the three adjoining streets, a feature so seldom secured. The machinery intake is on a wide street where the volume of traffic is comparatively small, which is favorable both for machinery handling and air supply. Boilers in an adjoining room will assist in the disposal of heated air from the substation by their combustion requirements and may also help to dispose of the cooling water.

Favorable conditions such as these are not to be had with all

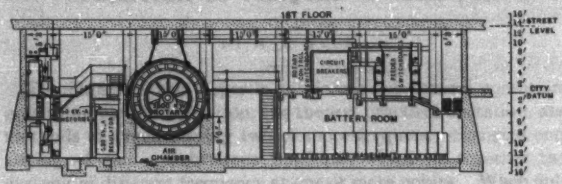


FIG. 13—SECTIONAL ELEVATION OF SUBSTATION SHOWN IN FIG. 12

sites secured, since many factors other than electrical or physical determine availability of locations, but withal the number and size of these prospective substations are rapidly increasing.

Because of the desire to treat these substations as a type, individual descriptions have been omitted and the characteristics of the type emphasized; for, with the increasing values of real estate in other large cities it is probable that this type of substation will awaken in the future a greater interest among electrical engineers.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 26, 1913.

Copyright, 1913. By A. I. E. E.

OPERATION OF FREQUENCY CHANGERS

BY N. E. FUNK

The object of this paper is to discuss the general conditions governing parallel operation, the theory, practical operation, and methods of synchronizing two or more frequency changers consisting of two synchronous machines which tie together two systems of different frequency at one or more points. When only one frequency changer is used to connect two systems, all of the difficulties experienced in the parallel operation of frequency changers disappears, as the operation then involves only connecting a synchronous motor to one system and a synchronous generator to the other. The only difficulty in this case is the adjustment of the frequencies of the two systems to permit synchronizing.

Before any definite idea of the method of performing an operation can be grasped, it is necessary to understand fully the underlying principles governing the phenomena in question. These principles must be reduced to their simplest value, which, while affecting the accuracy of the final result, still presents it in the most comprehensive manner.

General Conditions

1. Suppose the motors and generators of two frequency-changer sets are in synchronism, and the motors only are connected to the bus. Since these motors are synchronous machines, they will keep both units of each machine in phase. The generator of one set is now connected to the bus and slowly loaded, while the other generator is allowed to run light. If the synchroscope is connected to these generators before any load is on the bus, the indicator will assume a position showing synchronism.

As the load is increased, the synchroscope indicator will slowly move away from the position of synchronism, the angle of variation being roughly proportional to the load. This voltage lag angle is due to the magnetic lag of the armature and mechanical lag of the fields of the loaded machine due to load. If it is necessary to parallel the unloaded machine with the loaded machine, this machine switch must be closed with the synchroscope needle out of synchronism, since it will assume the same lag as the loaded machine when it carries its share of the load.

2. If one of the sets is running unloaded, and the other set is brought from rest to full speed, preparatory to synchronizing, it will be noted after both synchroscopes have been connected that when one synchroscope indicates synchronism, the other one may be at various different positions on the synchroscope face, and vice versa. If the systems are 60-cycle and 25-cycle respectively, there will be twelve different indications of the 25-cycle pointer for synchronous indications on the 60-cycle synchroscope, and five different indications of the 60-cycle pointer for synchronous indications on the 25-cycle synchroscope.

Theory

1. Any alternating-current apparatus containing a current-carrying winding through which magnetic lines are passing, is subject to induced voltage drops. The armature of an alternator is no exception to this general rule. The voltage at the terminals of an alternator carrying load is therefore less than the generated voltage, by the vector difference of the generated voltage and the resistance and inductance drop. Fig. 1 represents a single-phase generator and is self-explanatory, inasmuch as it is the conventional clock diagram showing the voltage drop in a circuit containing inductance and resistance. In Fig. 1 let E equal the maximum value of the terminal voltage, E_g the maximum value of the generated voltage, and I the maximum value of the load current.

ωL inductive ohms of armature. R resistance of armature. $\cos \theta$ power factor of load current. To make the problem as simple as possible, consider unity power factor. This corresponds to actual conditions, as frequency changers are operated at 100 per cent power factor wherever possible.

Fig. 2 shows the voltage relations in this system. The voltage E lags behind the generated E_g by an angle that is roughly proportional to the inductance of the armature times the load

carried; since the inductance is fairly constant this angle may be assumed to vary with the load. The effect of resistance in Fig. 2 is to reduce the terminal voltage but not to make any great change in the voltage lag angle. The resistance effect will therefore be neglected in the following discussion. If the generator is assumed to be operating as a synchronous motor, the effect will be the same as in Fig. 2 except that E and E_g will now change places since the counter e.m.f. of the motor is less than the bus voltage by the drop in the motor armature. Assume that the frequency-changer set consists of a 60-cycle motor driving a 25-cycle generator. Let K_1 equal the proportionality factor by which the load L may be multiplied to obtain the lag angle of the bus voltage behind the generator voltage, and K, the same factor for the motor. α_1^0 and α^0 are the corresponding lag angles. Assume the set is carrying a given load L. The counter e.m.f.

FIG. 1

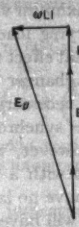


FIG. 2

of the 60-cycle motor will be α^0 behind the position it would assume at this instant if the motor were unloaded. $\alpha^0 = K\,L$. The field poles will be behind the position they would occupy at this instant if the machine were unloaded by $\alpha^0/p/2$ mechanical degrees, where p is the number of poles on the machine. The field poles of the 25-cycle machine are rigidly connected to the 60-cycle machine poles and are therefore the same mechanical degrees behind the position they would assume at this instant if the machine were unloaded. The maximum value of the 25-cycle generated voltage will occur

$$\frac{\alpha^0}{p/2} \times \frac{P_1}{2}$$

electrical degrees after it would occur if the machine were unloaded, p_1 being the poles on the 25-cycle machine. The bus voltage of the 25-cycle generator as in any generator will lag

behind the generated voltage by an angle proportional to the load. $\alpha_1^0 = K_1 L$. The maximum voltage of the 25-cycle bus will occur at an instant later than it would occur if the machine were unloaded by a time angle of

$$\alpha^0 \times \frac{P_1}{P} + \alpha_1^0 = L K \frac{P_1}{P} + L K_1 = L\left(K \frac{P_1}{P} + K_1\right) = \beta^0$$

and this lag angle will vary with the load. It should be understood that while the above relation is true only for unity power factor, it is a rough indication of what is happening in the armature of the set and is much more apparent than the complicated formula that illustrate actual conditions, which are given at the end of the article.

Having now established the fact that there is a time lag angle between the maximum values of the generated voltage when the machine is carrying load and when unloaded, the next step is to determine what effect this phenomenon will have in paralleling two frequency changer sets. If both sets were unloaded, it would only be necessary to parallel the machines when both 60-and 25-cycle synchroscopes indicate synchronism. Conditions change however, when it becomes necessary to parallel an unloaded set with a loaded set. The generator of the unloaded set will have no lag while the 25-cycle bus voltage of the loaded machine will have a time angle lag of

$$L\left(K \frac{P_1}{P} + K_1\right) = \beta^0$$

behind the position it would occupy if unloaded at this instant.

If the maximum voltage of the loaded machine is β^0 behind the position it would occupy if unloaded, and the maximum voltage of the unloaded machine coincides with the unloaded position of the loaded machine, then the unloaded machine must be ahead of the loaded machine by an angle β^0. It is necessary to close the 25-cycle switch of the unloaded machine when it is β^0 ahead of bus voltage in phase if it is to assume its share of the load.

If the 25-cycle machine were synchronized first, the indication of the 60-cycle synchroscope would show the motor voltage behind the 60-cycle bus voltage by an angle

$$\left(K_1 \frac{P}{P_1} + K\right) L = \beta^0,$$

This can be easily understood after a moment's thought. For, since the loaded 25-cycle bus voltage is behind the position it assumes at this instant if unloaded and the 25-cycle unloaded machine is in synchronism with it, but has no time to lag in its own armature or the armature of the 60-cycle machine connected to it, the time lag of the loaded machine is reflected in the 60-cycle synchroscope indication of the unloaded machine.

The synchroscope indications will be as shown in the diagrams, Figs. 3, 4, 5 and 6.

LOAD TRANSFERRED FROM 60-CYCLE TO 25-CYCLE BUS

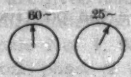


FIG. 3—60-CYCLE MACHINE SYNCHRONIZED FIRST

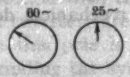


FIG. 4—25-CYCLE MACHINE SYNCHRONIZED FIRST

LOAD TRANSFERRED FROM 25-CYCLE TO 60-CYCLE BUS

FIG. 5—25-CYCLE MACHINE SYNCHRONIZED FIRST

FIG. 6—60-CYCLE MACHINE SYNCHRONIZED FIRST

These four indications are the only indications obtainable when it is correct to put both ends of the set in parallel. Of course, the angles indicated on the synchroscope will vary from zero at no load on the running machine to an angle depending upon the value of the inductance of the armatures of the 60- and 25-cycle machines of the set and the load carried.

VARIATIONS IN SYNCHROSCOPE INDICATIONS

If above phenomena were the only troubles incident to paralleling frequency-changing sets in which the frequency of one machine is not a multiple of the other, there would be nothing more to say about the matter, but as a matter of fact, the most annoying part of the operation, to the operator at least, is the fact that there is only one set of poles on the unit at which synchronism occurs at the same instant on both the 60- and 25-cycle synchroscopes. That is, only one indication in twelve on the 60-cycle and one in five on the 25-cycle is the correct one for paralleling.

Consider a 24-pole, 60-cycle machine connected to a 10-pole,

25-cycle machine. Assume that a positive machine pole has come to rest under the middle of one of the phase windings in each machine. This position will indicate synchronism on both synchroscopes. Now, turn the fields until the second 60-cycle positive pole assumes the position that the first pole assumed. The fields will have been turned through

$$\frac{360}{12} = 30$$

mechanical degrees. The 25-cycle machine poles will also have moved 30 mechanical degrees but since the positive poles are

$$\frac{360}{5} = 72$$

mechanical degrees apart, the positive pole will not be near the middle of the winding and therefore will indicate some other than synchronous position on the synchroscope. The following diagram (Fig. 7) indicates the relation these various pole positions bear to one another.

FIG. 7

The vertical lines above the horizontal line represent the middle of the positive poles on the 60-cycle machine and the vertical lines below the horizontal line represent the middle of the positive poles on the 25-cycle machine. Point 1 is the reference point and represents the middle point of an armature winding on one phase of each machine. The arrow indicates the direction in which the machines are supposed to be rotating. If the machines are revolving at the same speed and No. 1 point of both machines coincide, then both synchroscopes would indicate zero, but if No. 1 point of the 60-cycle No. 1 machine coincided with Point No. 6 60-cycle of No. 2 machine, then the nearest pole to No. 1, 25-cycle of No. 1 machine would be No. 3 pole of No. 2 machine which is $5 \times 30 - 2 \times 72 = 6$ mechanical degrees behind synchronous indication. If No. 2 machine is speeded up slightly then the 60-cycle needle will revolve five times before both No. 1 poles coincide, and the 25-cycle needle will revolve twice.

It is easily seen that at no point will be maximum value of the 25-cycle voltage occur simultaneously with the maximum value of the 60-cycle voltage except at zero or 360 which are one and the same point. To plot these indications on the face of the synchroscope it is necessary to construct a table showing the mechanical and then the electrical degree variations; considering first, synchronous indications on the 60-cycle synchroscope and then on the 25-cycle synchroscope. *O*, will be used to indicate synchronism, + or − indicates that the angle in question is clockwise or counter-clockwise from synchronous position. The tables are given below and in connection with the diagram will be readily understood when the first two steps are explained. Consider pole No. 1, 60-cycle. When this pole is under the middle of one phase of the armature winding the synchroscope indicates zero, the 25-cycle synchroscope will also show *O*, since No. 1 pole is supposed to be under the middle of one phase of the 25-cycle armature winding. Suppose that instead of No. 1 pole 60-cycle, No. 2 pole, 60-cycle was under the middle of the same phase winding. No. 1 pole, 25-cycle would then be 30 mechanical degrees behind the middle of the phase winding of the 25-cycle armature and be approaching it, therefore, it would be behind in phase relation or on the *slow* side of the synchroscope. Similarly No. 3 pole, 60-cycle would be at its maximum position when No. 2 pole, 25-cycle had passed the middle position of the reference line on the armature and therefore would indicate a leading phase position on the synchroscope; *i.e.*, the pointer, would be on the *fast* side of the synchroscope. The indications on the 60-cycle synchroscope are worked out in the same manner. (See Table II and Fig. 7).

The application of the data at hand is the next point to which to turn our attention. Suppose the set is being synchronized and the speed is slightly above synchronism. When the 60-cycle synchroscope shows synchronism, the 25-cycle is 90 deg. on the left hand side of the synchroscope face. Look in the table, and opposite −90 is found pole No. 4 on the 60-cycle machine. Since the machine is running fast this means that by the third time the 60-cycle pointer moves around the dial, the 25-cycle pointer will have reached synchronous position. If the machine were running slow, it would be necessary for the 60-cycle pointer to revolve 9 times before both synchroscopes showed synchronism. Instead of using the tables, it is much more convenient to construct a small indicator similar to a

synchroscope face and locate the values on this. As these markings will vary with the method of synchronizing, as will be explained later, the general methods of starting will be taken up and the use of the calculator illustrated for each case.

TABLE I

Pole No.	Syn. indications 60 ~	Syn. indications 25 ~ mech.	Syn. indications 25 ~ elec.	Pole No.	Syn. indications 60 ~	Syn. indications 25 ~ mech.	Syn. indications 25 ~ elec.
1	0	0	0	7	0	−36	−180
2	0	−30	−150	8	0	+ 6	+ 30
3	0	+12	+ 60	9	0	−24	−120
4	0	−18	− 90	10	0	+18	+ 90
5	0	+24	+120	11	0	−12	− 60
6	0	− 6	− 30	12	0	+30	+150

TABLE II

Pole No.	Syn. indications 25 ~	Syn. indications 60 ~ mech.	Syn. indications 60 ~ elec.
1	0	0	0
2	0	−12	−144
3	0	+ 6	+ 72
4	0	− 6	− 72
5	0	+12	+144

Methods of Starting

1. By induction motor or d-c. motor mounted on shaft of frequency changer set.

2. By using one of the machines of the frequency set as an induction motor.

First Method—Induction Starting Motor. This motor is usually of the wound rotor type. Suppose load is being transferred from the 60-cycle to the 25-cycle bus. The process of starting is as follows. The induction motor is put on the bus with all the resistances in the rotor, and as the machine comes slowly up to speed this resistance is cut out. The fields of both synchronous machines are put on and the 60-cycle field is adjusted to give 60-cycle bus voltage. It is impossible so to adjust the rotor resistance that exact synchronizing speed is obtained, since changes in resistance due to heating will change

the slip and the steps in the resistance would have to be very large in number with small values between the steps. Proper speed may be obtained by using the resistance step that gives the nearest value to synchronous speed and obtaining the finer adjustment by varying the 25-cycle field. This changes the iron loss in the 25-cycle armature and thus the load and slip on the induction starting motor. The 60-cycle machine will be synchronized first and then the 25-cycle machine will be put on, as it is more logical to connect the motor to the source of supply before connecting the generator to the load. It is now necessary to construct our synchronizing indicators before we can intelligently synchronize our machines.

These synchronizing indicators consist of small cardboard representations of the synchroscope face with a revolving disk attached. On this disk are shown the synchroscope pointer and the positions the pointer will assume at other than synchronous indications. In Fig. 8 the outer circle represents the stationary disk of the indicator while the inner circle is the revolving disk.

The outside circle, Fig. 8, is divided into 36 10-deg. spacings and these same divisions are marked on the 25-cycle synchroscope face. The inner movable disk is divided into 12 divisions corresponding to each position that the 25-cycle pointer assumes when the 60-cycle pointer indicates synchronism. The 10-deg. spacings are numbered arbitrarily and no numbers are used higher than 9 to save confusion when standing at a distance from the synchroscope. The 12 spaces on the moving disk are laid off as follows. (See Table I and Fig. 7).

When both 25-cycle and 60-cycle machines are in synchronism, the indication is as shown by the black synchroscope dial hand. When 60-cycle pole No. 2 is at No. 1 pole position, the 25-cycle pointer will have to move 150 degrees while the 60-cycle pointer moves around the dial once if the machine is running slightly above synchronism; therefore, the position marked 1 on the 25-cycle synchroscope means that the 60-cycle synchroscope pointer must make one more complete revolution before both will be in synchronism. If the machine were running slightly below synchronism, the correct pole for synchronizing would be moving farther away from the synchronizing position and it would be necessary for the machine to make a complete revolution relative to the running machine; therefore, the 60-cycle synchroscope pointer would be compelled to revolve 11 times before both pointers would indicate synchronism simultaneously.

In a similar manner, when No. 3 pole, 60-cycle is at No. 1 pole position, No. 2 pole 25-cycle is 60 degrees ahead in phase, and it is necessary for the 60-cycle synchroscope pointer to revolve 2 times fast, or 10 times slow before both are in synchronism. The 60-degree mark is therefore labelled 2 fast or 10 slow. The small arrows indicate the direction in which the needle is rotating. In this manner, all the other points are labelled.

In the first part of this paper, the lag angle due to load was explained. On the top of the stationary dial to the right and left are laid off the markings indicating the position of the pointer for various loads. The method of obtaining these load markings is given at the end of this paper.

To continue with synchronizing the machines. Suppose the amount of load carried by the running machines is X (See Figs. 8 and 3). Both synchroscopes are revolving slowly in the fast direction. Set the pointer to X, this revolves all the indications for other than synchronous positions as it should, since they are affected by load as well as the synchronous position of the pointer. Suppose the 25-cycle pointer lies between 8 and 9 (y) when the 60-cycle pointer shows synchronism (by inspection it will be seen that is the point 10←→2 will assume when the inner dial is shifted). This means that the second time the 60-cycle pointer rotates around the dial face and comes to synchronism is the proper time to close the 60-cycle switch. When this has occurred the 25-cycle pointer will occupy the position indicated by X. The 25-cycle field is then adjusted and after the starting motor has been taken off, the 25-cycle switch is closed, with the 25-cycle pointer about 22 deg. ahead of the bus in phase. The machine will assume its correct share of the load.

If instead of rotating fast, the synchroscopes had been rotating slowly, then the 60-cycle pointer would have rotated 10 times before the 25-cycle pointer would have reached X when the 60-cycle pointer indicated synchronism.

If the load was being transferred from the 25-cycle bus to the 60-cycle bus and the machines were synchronized in the same sequence as before, the point marked X_1 would be the proper indication of the 25-cycle pointer when the 60-cycle switch should be closed (see Figs. 6 and 8). The last method should only be used when there is some reason for not using the 25-cycle switch for synchronizing purposes.

Suppose that all the conditions of starting are the same as stated for the above, except that load is to be transferred from

the 25-cycle to the 60-cycle bus and that the 25-cycle machine, being the motor, is to be synchronized first. A new synchronizing indicator is necessary, and will show on the 60-cycle synchroscope the number of times that the 25-cycle pointer must revolve before the 25- and 60-cycle synchroscopes will indicate synchronism simultaneously. This indicator is constructed the same as Fig. 8, except that Table II and Fig. 7 are used. The load lag angle will be greater on the 60-cycle synchroscope than on the 25-cycle. Suppose for a given load the electrical degrees displacement are 10 in both armatures, the lag on the 25-cycle synchroscope is

$$10 \times \frac{5}{12} + 10 = 14.16 \text{ deg.}$$

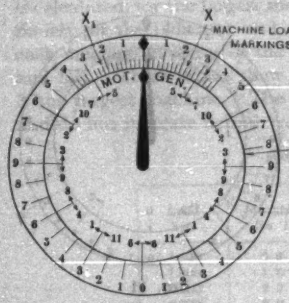


FIG. 8

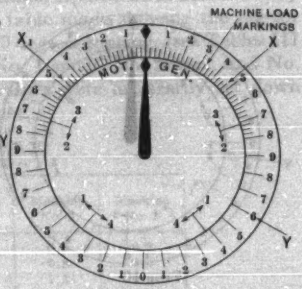


FIG. 9

and on the 60-cycle synchroscope is

$$10 \times \frac{12}{5} + 10 = 34 \text{ deg.}$$

The operation of synchronizing is the same as for Fig. 8, except 25-cycle is substituted where 60-cycle is used, and vice versa.

The only difference in operation where a d-c. starting motor is used is that it is possible to obtain correct synchronous speed by adjusting the d-c. motor field and it is therefore unnecessary to use the synchronous generator field as a speed adjusting medium.

Second Method. Assume the 60-cycle machine acting as a motor and load being transferred from the 60-cycle to the 25-

cycle bus. The 60-cycle machine is started at reduced voltage by an auto-starter or some other means. When the machine has reached full speed the field is put on both units. It is now necessary to construct a synchronism indicator since only one synchroscope will be available for synchronizing. The 25-cycle synchroscope will be laid off as before, the only difference being that the markings now indicate the number of times the 25-cycle pointer must pass synchronous indication before the proper synchronizing point is reached. This may be constructed from table I and Fig. 7, or from Fig. 8 by multiplying the numbers on the dial by 5/12 and discarding the remainder. The closing of the 60-cycle motor field locks the set in synchronism on the 60-cycle side. Suppose the 25-cycle pointer is at y, this cor-

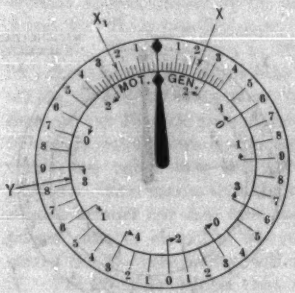


FIG. 10

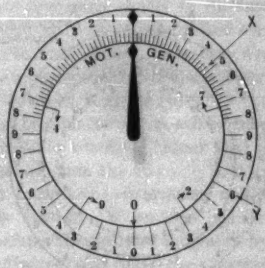


FIG. 11

responds to 1 on the revolving dial when the pointer has been placed at X. The field of the 60-cycle motor is now taken off and the 25-cycle pointer will begin to revolve in the slow direction. When it has passed synchronous position once and reached the point 0, the 60-cycle field is again closed, which locks the motor in synchronism. The 25-cycle pointer will now stand at X.

The 60-cycle machine is thrown from starting to running voltage taps and the 25-cycle machine switch is closed. If all conditions were the same ,but the load were being transferred from the 25-cycle bus, the indicator pointer would be set at X_1, but all the operations would be the same, assuming the 60-cycle machine was the one equipped with the starting device. If the 25-cycle machine was equipped with the starting device, the operation would be the same as before, assuming that the load transferred

from 25-cycle to 60-cycle bus, 25-cycle inserted for 60-cycle and vice versa. The synchronism indicator shown in Fig. 11 would then be used, showing indications on the 60-cycle synchroscope of the number of times the 60-cycle needle must pass synchronous indication before the proper time for synchronizing. Fig. 11 is obtained from Fig. 9 by multiplying by 12/5 and dropping the remainder, or from Fig. 7 and Table II.

All instances in the above cases have depended on the assumption that there was the same percentage inductive drop in the armatures of both sets.

A difference in size can be accounted for on the indicator as follows. If the running machine is one half size, take twice the load it is carrying on the indicator, assuming that the indicator is calculated, for the largest machine, or the load indications may be left off the indicator and a table made showing the lag for each machine in terms of the 10 degrees spacing, (see Tables III and IV). These tables show No. 1 small, No. 2 next, and No. 3 the largest machine. The values were arbitrarily set down and do not indicate actual values.

TABLE III
25 ~

Load kw.	Machine No. 1	Machine No. 2	Machine No. 3
500	0.8	0.4	0.2
1,000	1.6	0.8	0.4
1,500	2.3	1.1	0.6
2,000	2.9	1.5	0.8

TABLE IV
60 ~

Load kw.	Machine No. 1	Machine No. 2	Machine No. 3
500	1.9	0.9	0.5
1,000	3.8	1.9	0.9
1,500	5.5	2.7	1.4
2,000	6.9	3.5	1.9

Effect of Different Percentages of Armature Inductance on Parallel Operation of Frequency Changers

If the machines have different percentages of inductive drop, then when all are in parallel, they will not share the load equally. This may be overcome by arranging one of the armatures of each

set so that it may be revolved, and by shifting the various armatures it is possible to make the machines share the loads equally at some one point, but in this event the machines will not share the load satisfactorily if load is transferred in the reverse direction. For example, consider the inductance of one machine such that the generator and motor voltages have a time lag of 10 mechanical degrees at full load over the no load value, the other machine 15 mechanical degrees. If these machines are in parallel, the lag angle must be the same in both, and if we consider the angle proportional to the load, No. 2 machine will only carry 66 per cent of full load when No. 1 is fully loaded. To enable the machines to divide the load evenly it would be necessary to shift No. 2 motor armature ahead, or No. 2 generator armature back, considering direction of field rotation as forward movement. If the direction of power transfer was now interchanged the machines would not share the loads as well as before

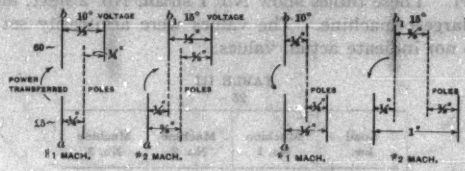


FIG. 12

the armatures were moved. Fig. 12, while not mathematically correct, shows clearly why this is so.

In this figure, a and b are the mid-points of the armature windings of the machine with a 10-degree lag angle represented by $\frac{1}{4}$ in., and a_1 and b_1 are the mid-points of the armature of the machine with a 15-degree lag angle represented by $\frac{3}{8}$ in. Suppose power is transferred from 25-cycle to 60-cycle bus. The lag in the 25-cycle armature is $\frac{1}{4}$ in. (this is the mid-point of the poles). The lag in the generator armature is $\frac{1}{4}$ in., thus making the amount the 60-cycle voltage lags $\frac{1}{2}$ in. In machine No. 2, the armature is moved ahead $\frac{1}{4}$ in. and the lag of the motor armature is $\frac{3}{8}$ in. (this is the mid-pole position). The generator armature lag is $\frac{3}{8}$ in. making a total of $\frac{1}{2}$ in., and since these two angles are the same, the machines will each take their share of the load. If the direction of power transfer is reversed, No. 1 machine still shows a lag of $\frac{1}{2}$ in. but No. 2 is $\frac{3}{8}$ in. on the

motor end, $\frac{3}{4}$ in. on the generator end plus $\frac{1}{4}$ in. that the armature has been moved, making 1 in. or twice the lag of No. 1 machine, in consequence No. 1 will carry 140 per cent load and No. 2 will carry 60 per cent load, assuming machines to be of equal capacity and the total load equal to the combined capacity of both machines.

$$X = \text{No. 1 machine load}$$

$$Y = \text{No. 2 " "}$$

$$\frac{X\,\frac{1}{2}}{100} = \frac{\frac{3}{4}\,Y}{100} + \frac{1}{4}$$

$$X + Y = 200$$

$$\frac{1}{2}\,\frac{(200 - Y)}{100} = \frac{\frac{3}{4}\,Y}{100} + \frac{1}{4} \times \frac{100}{100} = \frac{\frac{3}{4}\,Y + 25}{100}$$

$$100 - \frac{Y}{2} = \frac{3}{4}\,Y + 25$$

$$75 = \frac{5}{4}\,Y$$

$$Y = \frac{4}{5} \times 75 = 60$$

$$X = 200 - 60 = 140$$

This shows that great care must be taken in writing the specifications for purchasing frequency changers, that are to transfer load alternately from one frequency to another, and still greater care in designing them. For while it is possible to arrange the set so that the load will be properly divided at some specific point when transferring load in a given direction, no matter if the per cent inductance varies considerably, the sets will not operate satisfactorily when the direction of load transfer is reversed. This statement of course, applies only to the case where two sets are operating in parallel in the same station, as where two systems are tied together by two frequency changer sets located in different stations, the line inductance determines

to a great extent the proper division of the load. With only one set connecting two systems, however, the phase angle of the frequency changer set has nothing to do with the amount of load it carries. The amount of load being determined in this case by the governor settings of the prime movers of the respective systems.

Formulas for Phase Angle Variations of Frequency Changer Units

$\omega L I$ = Inductive voltage drop in motor armature, at load I
$r I$ = Resistance " " " " " " " "
I = Load current of motor.
E = Bus voltage, motor.
θ = Power factor angle, motor.
α = Lag angle, motor.
f = Motor frequency.
f' = Generator "
α' = Lag angle, generator.
θ' = Power factor angle, generator.
E' = Bus voltage, generator.
I' = Load current, "
$r' I'$ = Resistance voltage drop in generator armature at load I'.
$\omega' L' I'$ = Inductive voltage drop in generator armature at load I'.

$$L = \frac{\omega L I}{E}$$

$$R = \frac{r I}{E}$$

$$L' = \frac{\omega' L' I'}{E'}$$

$$R' = \frac{r' I'}{E'}$$

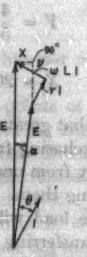


Fig. 13

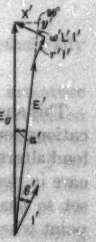


Fig. 14

α_t = the total phase angle of generator.

$$\cos \alpha = \frac{E - Y}{\sqrt{(E - Y)^2 + X^2}}$$

$$Y = r\,I\cos\theta + \omega\,L\,I\sin\theta$$

$$X = \omega\,L\,I\cos\theta - r\,I\sin\theta$$

$$\frac{r\,I}{E} = R$$

$$\frac{\omega\,L\,I}{E} = \mathbf{L}$$

Substituting,

$$\cos\alpha = \frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2\,(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$

$$\cos\alpha' = \frac{E' + Y'}{\sqrt{(E' + Y')^2 + X'^2}}$$

$$Y' = r'\,I'\cos\theta' + \omega'\,L'\,I'\sin\theta'$$

$$X' = \omega'\,L'\cos\theta' - r'\,I'\sin\theta'$$

$$\frac{\omega'\,L'\,I'}{E'} = \mathbf{L}'$$

$$\frac{r'\,I'}{E'} = R'$$

Substituting,

$$\cos\alpha' = \frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}}$$

$$\alpha_T = \alpha\,\frac{f'}{f} + \alpha'$$

$$\alpha = \cos^{-1}\frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2\,(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$

$$\alpha' = \cos^{-1}\frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}}$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1 - R\cos\theta - \mathbf{L}\sin\theta}{\sqrt{1 - 2(R\cos\theta + \mathbf{L}\sin\theta) + R^2 + \mathbf{L}^2}}$$

$$+ \cos^{-1}\frac{1 + R'\cos\theta' + \mathbf{L}'\sin\theta'}{\sqrt{1 + 2\,(R'\cos\theta' + \mathbf{L}'\sin\theta') + R'^2 + \mathbf{L}'^2}} \qquad (1)$$

It is usual to operate frequency changer sets at unity power factor. Therefore

$$\cos\theta = \cos\theta' = 1$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1-R}{\sqrt{1-2R+R^2+L^2}}$$

$$+\cos^{-1}\frac{1+R'}{\sqrt{1+2R'+R'^2+L'^2}} \qquad (2)$$

The resistance drop at unity power factor has its greatest effect in varying the voltage but only a small effect in varying the lag angle, let us therefore assume that the resistance is zero.

$$R = R' = 0$$

$$\alpha_T = \frac{f'}{f}\cos^{-1}\frac{1}{\sqrt{1+L^2}} + \cos^{-1}\frac{1}{\sqrt{1+L'^2}} \qquad (3)$$

Assuming that the angles are small, we can see from Fig. 15 that they are proportional to L and L' which are proportional to the loads as we assumed in the beginning of this article.

FIG. 15

$$\therefore \alpha_T \propto \text{load}$$

METHOD OF OBTAINING LOAD READINGS

It is possible, if the constants of the machines are known, to obtain the markings on the synchronizing indicators by calculating from formula (1) or fairly accurate results may be obtained from (2) or (3), but the best and most practical way is to run one machine loaded and another one with only the motor connected. The generator synchroscope is then put on and the indications of the pointer are noted for various loads on the running machine. These readings may be plotted on the indicator or in a table as shown earlier in this paper. There are many more interesting points in the operation of frequency changers, but the object of this article was to deal only with the synchronizing of these machines.

DISCUSSION ON "AUTOMATIC SUBSTATIONS" (SUMMERHAYES), "CONVERTING SUBSTATIONS IN BASEMENTS AND SUB-BASEMENTS" (JAMIESON) AND "OPERATION OF FREQUENCY CHANGERS" (FUNK), COOPERSTOWN, NEW YORK, JUNE 26, 1913.

D. B. Rushmore: I will bring up certain points of unusual interest in the situation brought forward in Mr. Summerhayes's paper on automatic substations, because of the possible large development along this line. There is such a large field of application of electric energy, and such a large field of undeveloped sources of power now awaiting the man who can reduce the cost of operation, either of application or development, that it is an interesting subject to consider.

In a great many places there are operating conditions in which an automatic substation would allow electricity to be used where otherwise it would be uneconomical, and in the big field of agricultural operations, it would appear that there might be considerable use of such installations. There is already in existence a small substation in which the machinery is supposed to run indefinitely. Mr. Moody has put a continuous-running substation on a pole, without any attendance, and put a revolving machine there which is supposed to run indefinitely, almost without inspection. In mining work, especially, and in work subject to labor disturbances, the advantages of automatic substations are very evident, and it is very interesting to look forward and see the possible growth of this work.

F. D. Newbury: Mr. Summerhayes's paper is an interesting solution of a very difficult problem. I would like to hear, though, from some of the operating men, as to their feeling in connection with the operation of fairly large machines without superintendence at all times. There has been, of course, a large amount of remote-control machinery installed, but it has been, in general, in relatively small capacities and of course, in practically all cases the machinery has been of the non-commutating type. Remote control is certainly in the direction of economy, and it will undoubtedly continue to develop. It is, moreover, directly in line with the extensive use of outdoor transformer and oil switch substations, which two or three years ago were looked upon with a good deal of skepticism, if not disfavor.

There are two minor points in the paper I would like to refer to. The possibilities of the converter coming up with the wrong polarity is nicely taken care of in this case by separately exciting the converter. Separate excitation, however, will not be generally available. This is particularly true of railway substations that do not have a storage battery or other direct-current source of supply.

The two-thirds voltage switch also is mentioned, but I do not believe that that additional application is necessary—certainly not in the 500-kv-a. converter—and the switching could be

considerably simplified by using only one starting voltage instead of the two.

In Mr. Jamieson's paper, I wish to emphasize from the designer's standpoint the necessity for an adequate supply of cool, clean air. As Mr. Jamieson well points out, it is difficult to obtain, but it is absolutely necessary to the life of the machines if they are to be operated at a rate that is at all economical. With substation air temperatures of 40 deg. or 45 deg. very little is left between that and a permissible 90 deg. for temperature rise in the apparatus.

In connection with the cleaning of the air, Mr. Jamieson mentions an ingenious vacuum air filter. Several air washing outfits have been developed and have been used to a limited extent in this country and quite extensively abroad. That, I should think, would be particularly adapted to the restricted space of substations in basements, and I would like to know if it has been applied to that work.

In connection with Mr. Funk's paper, while it is somewhat outside the range of his paper, I would ask if he has had any experience with the use of pumps in order to introduce oil pressure under the bearings before starting, in order to facilitate starting. That has been considered, and I know such a system has been installed. If he has had any experience with such an outfit I would be glad to know the results.

F. C. Caldwell: In connection with the paper on automatic substations, I would call attention to the fact that an automatic resetting circuit-breaker is now being developed and will shortly be on the market. This breaker, of course, opens when there is an overload and then will not close again until the overload goes off of the direct-current circuit. As soon as this happens the breaker closes and is again ready for operation.

Paul M. Lincoln: I am reminded by Mr. Summerhayes' paper of the old saying that the proof of the pudding is in the eating, and not in the chewing of the strings of the pudding-bag. I consider that our getting up here and talking about this matter of distant operating substations is considerably in the nature of the chewing of the strings of the pudding-bag. The crux of the matter lies in how it operates, and whether it gives satisfaction to the operators, and whether it is cheap. We are told by Mr. Summerhayes it has been in operation for some time and gives promise of being a solution of the problem of substations operated without attendance. I trust so, and I believe that Mr. Summerhayes is to be congratulated on working out the details of the automatic substations so completely.

H. M. Hobart: As to Mr. Newbury's suggestion about washing the air, it may be interesting to mention that the London Electric Supply Station at Deptford has several large turbo-generators, of 5000 kw. each, which supply the London, Brighton & South Coast Railway with power, and the air is being washed by being passed through sprays of water. This is the largest

installation of this character, I believe. Water filters are also used for washing the air supplied to the turbo-generators of the Brighton Electricity Supply Corporation. The system performs the additional function of cooling the air, as well as washing it. If the air is cleaned by filtering it through cloth screens the screens gradually become clogged up, and the machines will get very hot, until the screens are cleaned, whereas by passing the air through water sprays nothing can get out of order.

Henry W. Peck: Mr. Summerhayes's paper was very interesting to me, as I have had some operating experiences along the lines dealt with in the paper.

Regarding Mr. Newbury's suggestion, I would have little hesitation in applying such a system in certain cases. In the stations the trouble comes so quickly that even if you have an operator you are relying on the automatic regulation to protect the station and the system. If the automatic equipment does not work, your main station, or the equipment of it, is apt to be seriously damaged even if you have attendants there.

I would like very much to have Mr. Summerhayes work out this idea along the line of our discussion yesterday regarding synchronous condensers. It might be somewhat more difficult than the station which he describes in his paper, but I am not sure that it would be. You would then obviate the difficulty suggested yesterday of having inefficient operators with whom to trust the operation of the synchronous condensers. Thinking it over very briefly, I can see no difficulty in arranging automatic devices to get the desired effect of field strengthening or weakening to vary with the conditions. It seems to be no more difficult than some things which our designing engineers have accomplished. The economy of such an automatic station is especially great in view of the feeling on the part of operating men that more than one man must be present in any building which contains high-tension or even moderate tension electrical apparatus. The presence of two men in the station is required in some states by law, or city ordinance. Many companies feel it is not safe, even though there is no law requiring it, to have less than two in the station. This means that even in a small station, where there is not enough to keep one man busy one-quarter of his time, we must have two men present at all times. The economy, therefore, of a station without attendants is exceedingly great.

S. D. Sprong (by letter): This paper presents a rather novel adaptation of standard apparatus as a commercial expedient. The plans as shown reveal a very careful working out of the elements of the problem and an excellent judgment in the selection of the automatic devices to meet the unusual condition of absence of manual operation and immediate supervision.

It is, however, this very complete provision for remote control and automatic means to prevent damage to the apparatus that emphasizes the point which the author seems to consider of

paramount importance. I refer to the fact that there is apparently no special thought or provision to safeguard the service even though at the possible expense of the equipment. Continuity of service, especially in an underground district of this character, should have first consideration under all conditions and it is a frequently emphasized rule among most light and power companies to maintain service even when it may probably result in damage to apparatus or equipment. The author appears to take quite the contrary view in that all the automatic and other provisions for meeting emergencies are designed to safeguard the apparatus, which exaggerates much beyond its true relative value the safety of the equipment as compared with the maintenance of service. I believe that any section of the city that would justify the installation of an underground d-c. system, is of such importance as to justify the relatively small additional expense of substation operators, the wages of which when capitalized would secure more of the elements that go to the maintenance of satisfactory service and the meeting of emergency conditions than any elaboration or duplication of automatic safety devices and methods of remote control.

I would suggest as an alternative, the employment of a substation operator covering a ten-hour period from 4 p.m. to 12 midnight, which would cover the heavy load period, and during the remaining fourteen hours and Sundays the lighter load could be carried by trunk feeders from one of the regular substations and controlled by pressure wires. Assuming the low load factor of 25 per cent this would give about 1,000,000 kw-hr. output per year. With a labor cost for the single operator of about $800 it would show about eight hundreths of a cent per kw-hr. additional cost on the whole consumption in this district. As the character of the load in this district is almost entirely retail and therefore at the maximum rate, an additional output cost of eight tenths of a cent would be more than offset by the numerous advantages to be obtained in such a district by having an operator in charge during important hours of the load.

H. R. Summerhayes: Mr. Newbury referred to the possibility of operating large machines without attendance. I think that large machines are possibly more reliable than small ones. It is only on account of the larger investment involved that people would hesitate to extend this principle to very large machines. Where the investment is so large that you can afford to have an operator on account of certain hazards, such as the fire hazard, for instance, the advantage of this form of automatic operation is not so great as in cases where the attendant is not required on account of the fire risk. So far as the operation of a machine is concerned, I should think the larger machine is fully as reliable as the smaller one.

In reference to the matter of polarity, also brought up by Mr. Newbury, Mr. J. B. Taylor devised several years ago a polarized relay to be connected across the commutator, across the brushes,

and as the machine goes up to synchronism, that relay would be getting alternating current. As it came very near synchronism, it would be polarized current, and the relay would be prevented by a dashpot, from going to its full travel. It would not operate finally, until synchronism had been obtained, when direct current would be supplied to it, and then it would operate in a direction determined by the polarization of the relay.

J. C. Lincoln: Suppose it happens to get in synchronism, so the relay was kept out, what is there to make the relay slip forward?

H. R. Summerhayes: It will be arranged to reverse the connections so that it is connected to the bus in the right direction.

Mr. Newbury brought up the point of the two-thirds voltage switch. When we first laid out this remote power plant, we started on one voltage, and threw on all the voltage, but it was thought desirable to put in an extra switch, because we were not sure at first exactly what field strength would have to be used, and as a matter of fact, we can go through from one-third voltage to full voltage without creating any disturbance, but in order to do so we must first make the full field, which can be done, but the field on this machine is so strong that there is somewhat more disturbance in throwing over with a strong field than by the method used.

Mr. Peck referred to the operation of synchronous condensers automatically, that is, automatically restarted, I suppose. I think a synchronous condenser can be arranged so as to be operated by an automatic voltage regulator, and operated practically without attention. Either that, or a synchronous motor can be arranged so that if the power goes off the transmission line, and then comes back again, the motor can be restarted. I know of a case now where it is planned to put in a restarter for a synchronous motor. In this case a town is lighted by a frequency changer, a 60-cycle line, the synchronous motor driving this set being supplied from a 25-cycle transmission line. The apparatus is modern and the operator does not spend much time in the station, but is able to give a large part of his time to other duties. Everything operates all right except when the power goes off the line, and then the frequency changer shuts down and the operator must go back and start up. I proposed an equipment for that station so arranged that when the motor falls out of step it will be thrown on the starting taps, so that when the power comes back it will be automatically restarted, and the proper arrangements for field and load will be taken care of automatically.

Mr. Lincoln asked if the operation is satisfactory. I do not know whether there are any of the Detroit Edison people here, but Mr. Cato intended to be here. I recently talked with Mr. Cato and he said he has not heard from the station for a long time, that they send a man there once a day to inspect it, and he has not heard any complaint regarding the station, and that it operates satisfactorily.

As to the heating of the building, this substation in Detroit is not heated, and that expense is saved as well as the expense of the operator.

D. W. Roper: The only question raised, I believe, was as to the cleaning of the air supply, suggesting that this be done by washing rather than by screening. In the substations covered by Mr. Jamieson's paper, the limitation, I believe, has been generally found to be one of space, for the washing scheme requires more space than the air screening system. The washing system has been tried in one or two of the smaller installations, and the reason for its lack of success was because there was not sufficient space for a proper installation. However, if a screen device with a vacuum cleaner can be worked out, it would appear to be simple and require less attention than the washing scheme.

N. E. Funk: Concerning the oil pressure supply to the bearings to make the machine start easily, in the case of the two machines I have in mind, one 3000 kw. and one 6000 kw., it was not necessary to use oil pressure in the bearings of the small machine, as it started easily. It was impossible to start the 6000-kw. machine with a 600-h.p. motor consuming about 1200 kv-a. unless an oil pressure of 150 lb. per sq. in. was applied for about 3 min., and then it started very slowly. If oil pressure was applied for about 5 min. a crack was heard in the bearings indicating that the shaft had lifted from the bottom of the bearing, and the machine started easily.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

Copyright, 1913. By A. I. E. E.

THE ELECTRIC STRENGTH OF AIR—IV

BY J. B. WHITEHEAD AND T. T. FITCH

I. Introduction

This paper describes the results of a series of investigations on the effects of pressure, temperature and density of gas upon the formation of the corona in air. It is largely an extension of work described in the second of this series of papers.

The study of the influence of temperature and pressure on corona-forming voltage was begun by Ryan in 1904. The influence of pressure in its relation to the size of conductor was shown in the second of this series of papers. The influence of temperature and pressure has been investigated also by Peek who has given an interesting empirical formula connecting critical corona intensity in air with pressure, temperature and size of conductor. The influence of pressure on critical corona intensity has been studied by Watson for the case of continuous voltage. The purpose of the present work has been the extension of the earlier investigations both as to range of pressure and size of conductor and also to obtain further information on the influence of temperature. Some observations were also made with carbon dioxide as the gas surrounding the conductor instead of air to see what part, if any, is played by the density of the gas.

The larger part of the work is the study of variation of critical or corona-forming intensity with pressure. For this work conductors varying from 0.438 to 0.950 cm. in diameter were used, and the pressure was varied from 5 to 110 cm. of mercury.

II. Review of Earlier Work on Pressure and Temperature

A brief review of earlier investigations on the variations of critical intensity with pressure and temperature will not be

out of place. Some other points, also, have such an intimate relation to these variations or at least to a study of them that they will be mentioned.

It was shown by Ryan[1] that for the one size of conductor which he used, the critical intensity is a linear function of the pressure from 40 to 90 cm. of mercury. A similar relation was shown to hold for variations with temperature between 21 and 93 deg. cent.

Watson published a set of experiments[2] in 1909 showing a linear relation between pressure and critical intensity for the case of continuous voltage. His range of pressure was from 36 to 76 cm. of mercury and of size of conductor from 0.07 to 0.95 cm. He also gave curves showing the amount of current passing.

In the earlier papers of this series numerous curves were given showing a linear relation between critical intensity and pressure from 38 to 100 cm. The conductors used ranged in diameter from 0.122 to 0.475 cm. Some experiments were also made showing a linear relation between critical intensity and temperature. Only one size of conductor was used. The range of temperature was from 8 to 41 deg. cent.

It has further been shown in these papers that:

The critical intensity is independent of free ionization, moisture content and velocity of the air.

The visual critical intensity is identical with that determined by an electroscope.

The critical intensity g for clean round conductors for a pressure of 76 cm. and temperature of 20 degrees may be expressed by the formula:

$$g = A + \frac{B}{\sqrt{D}} \tag{1}$$

where A and B are constants and D is the diameter of the conductor. This formula is discussed in a later paragraph.

Peek[3] has given the results of a [illegible] of experiments on the variation of critical intensity with temperature showing practically a linear law between -20 and $+140$ deg. cent. He has also given a general formula covering the variations of critical

1. Ryan: *Conductivity of the Atmosphere at High Voltages*, TRANS. A. I. E. E., Vol. XXIII, 1904.
2. *Electrician*, Vol. LXIII, 1909.
3. Peek: *The Law of Corona*, TRANS. A. I. E. E., Vol. XXXI, 1912.

intensity with change of temperature and pressure for a tube and concentric conductor as follows:

$$g = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta\, r}}\right) \qquad (2)$$

where g is the critical intensity in kilovolts per cm., r is the radius of conductor and

$$\delta = \frac{3.92\,p}{273 + t}$$

p being the pressure in cm. of mercury and t the temperature centigrade. So far as we can find, the only statements he has given concerning the influence of pressure on the variation of critical intensity are a curve[4] giving observations on a 2.54-cm. conductor for pressures from 2 to 65 cm. and a table of values of δ and corresponding values of g in closing the discussion of his 1912 paper.[5] No description of his methods was given.

III. Present Work

The observations which are recorded in this paper were made in the spring of 1912. They aim to supply, in part, the lack of sufficiently extensive data on variation of critical corona intensity with pressure and size of conductor.

Apparatus and Equipment. For the pressure measurements a 20-cm. iron tube about 90 cm. in length was used. The ends were fitted with insulating caps about 18 cm. long. These caps were made of impregnated fibre, and served the double purpose of insulation and sealing for the variation of air pressure both above and below that of the atmosphere. A rotary air pump permitted evacuation of the tube to about five cm. of mercury in five minutes. Most changes of pressure could be made in a minute or two, but owing to numerous joints necessary for insulation purposes there was present some leakage, which necessitated a longer time to exhaust to the lowest pressure reached, and set the limit of about five cm. as the minimum.

A small glass window was placed in the tube for making visual observations of the corona, but during most of the work the gold leaf electroscope was used for detecting the point at

4. Peek: "Nature of Corona," *Gen. Elec. Review*, December, 1912.
5. Peek: *The Law of Corona*, Trans. A. I. E. E., Vol. XXX, 1912.

which corona begins. This method has been described in detail in the first of these papers, so no further description is necessary here. Fig. 1 shows the general arrangement of the apparatus. The beginning of corona is very sharply defined. A change of one per cent or less in the voltage will cause the time of complete discharge to change from about a half hour to five seconds. Any difference between the beginning of corona as observed by the eye and by the discharge of the electroscope is within this small error of observation.

The observations on the influence of temperature were made with a similar apparatus, except that the tube was in this case surrounded by a water jacket. Hand stirring of the water was found to be sufficient to keep the temperature of the air within the tube uniform to about two degrees. Only the smaller sizes of conductor could be used in this apparatus owing to spark-over troubles occasioned by the reduced size of outer tube. The heating was done by gas burners and ice was used for getting reduced temperature.

Source of Power. The power for all the experiments was drawn from a 10-kw., 100,000-volt transformer. The transformer was operated by a motor-generator set of 7.5 kw. capacity, the generator field being excited by a storage battery, resulting in good voltage control. All experiments were made at a frequency of 60 cycles. The transformer is provided with a

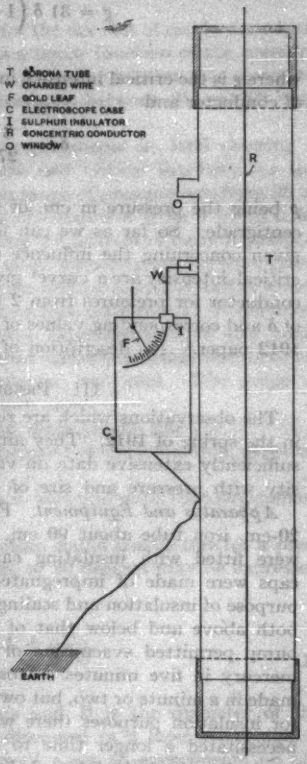


FIG. 1—ARRANGEMENT OF APPARATUS

test coil giving 120 volts for 100,000 volts on the high-tension terminals as computed from the ratio of primary and secondary turns. This test coil was used entirely in making measurements of the voltage. All determinations of ratio of maximum to mean effective voltage were also obtained from this coil.

Ratio of Maximum to Mean Effective Voltage. For the purpose of checking the results this ratio was determined by two methods. The first makes use of the oscillograph, the second of a rotating contactor and the principle of the potentiometer.

The ratio was determined from the oscillograms by reading a number of ordinates, usually about 30 or 40 to a cycle. From these ordinates taken at equal distances the ratio of maximum to the square root of the mean square value was computed. The principal difficulty with this method is to obtain an oscillogram with lines sufficiently sharp and narrow.

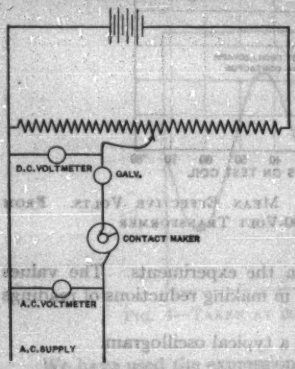


FIG. 2—METHOD OF MEASURING RATIO OF MAXIMUM TO MEAN EFFECTIVE VOLTAGE

The contactor method is indicated in Fig. 2, the contact wheel being placed on the generator shaft. In the actual apparatus a handle was provided for readily shifting the point of contact. By reference to the galvanometer the contact can be shifted until the closure occurs on the peak of the wave. Then the slider on the rheostat is moved until the galvanometer indicates zero deflection. The readings of the continuous and alternating voltmeters are then taken. The ratio of their readings in volts is the ratio desired, the direct-current voltmeter indicating the maximum voltage and the alternating-current voltmeter the mean effective value.

The chief difficulty with this method is to keep the source of alternating voltage sufficiently steady during the time necessary for an observation. A damped galvanometer of fairly high sensibility is required. Only the relative calibration of the voltmeters is necessary since the ratio is all that is required. The alternating voltmeter used was of the electrodynamometer

type and it was compared with the direct-current voltmeter by taking the mean of readings with reversed polarity.

Table I, of which Fig. 3 is a plot, gives the ratio of maximum to mean effective voltage for the various voltages on the test

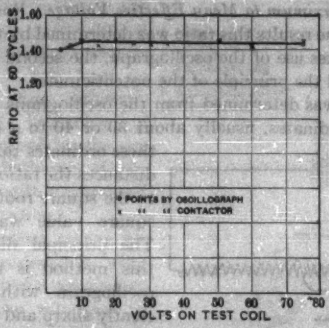


FIG. 3—RATIO OF MAXIMUM TO MEAN EFFECTIVE VOLTS. FROM TEST COIL OF 100,000-VOLT TRANSFORMER

coil of the transformer used in the experiments. The values taken from the curve were used in making reductions of readings on critical intensity.

Fig. 4 is a reproduction from a typical oscillogram.

TABLE I

Test coil volts	Ratio = Max. / Mean eff.		
	Contactor	Oscillograph	From curve
4		1.395	1.400
7		1.420	1.420
10		1.450	1.440
15	1.431		1.440
20	1.459		1.445
25	1.436		1.445
30	1.429		1.445
35	1.438		1.445
50	1.444	1.446	1.440
60	1.431	1.430	1.440
75	1.452	1.427	1.440

Variation of Critical Intensity with Gas Pressure. Fig. 5 shows the observed variation of critical corona voltage with pressure, while Fig. 6 shows the corresponding variation of critical intensity computed from the same observations. As mentioned before, nine conductors varying from 0.238 to 0.950 cm. in diameter were used. Above 30 or 40 cm. pressure the curves are nearly straight; the curvature being so slight as to be within the error of observation. They explain, therefore, the conclusion of the earlier paper that the relation between pressure and critical intensity is linear in this region.

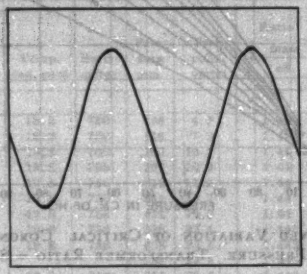


FIG. 4—TAKEN AT 60 CYCLES AND 60 VOLTS

We have used the expression

$$\frac{dv}{dr} = \frac{E}{r \log \frac{R}{r}}$$

for calculating the critical intensity in kilovolts per cm. from the observed critical voltage on the transformer test coil. E is the maximum voltage on the conductor obtained by taking into account the ratio of transformation of the transformer, and the ratio of maximum to mean effective voltage, while r and R are the radii of conductor and tube, respectively.

Table II gives a typical set of observations.

Several readings were taken at each pressure as shown in the readings for the last three pressures. The pressure was determined by use of a gauge or monometer. This method gives, of course, only the difference of pressure between that in the tube

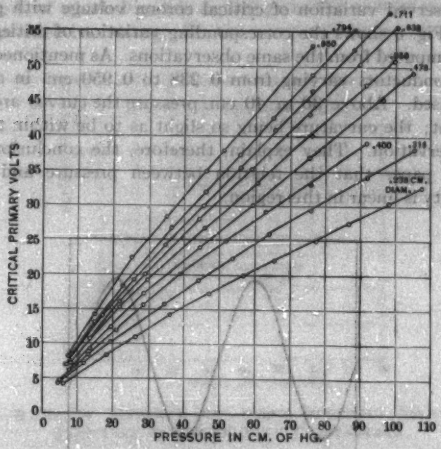


FIG. 5—OBSERVED VARIATION OF CRITICAL CORONA VOLTAGE WITH PRESSURE. TRANSFORMER RATIO = 833

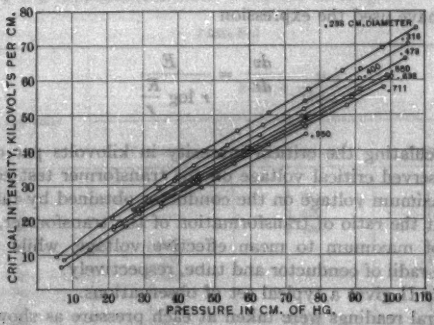


FIG. 6—VARIATION OF CRITICAL INTENSITY WITH PRESSURE AND SIZE OF CONDUCTOR AT 20 DEG. CENT.

and atmospheric. For this reason it was necessary to read the barometer to obtain the absolute pressure. The voltage was read by two Weston alternating-current voltmeters of suitable ranges connected to the test coil of the transformer, as stated. In taking readings the electroscope was first charged and then the voltage gradually raised till the electroscope was suddenly discharged, as shown by the fall of the gold leaf. Atten-

TABLE II

Diameter of conductor 0.316 cm. Transformer ratio 833 $\frac{1}{r \log R/r} = 1.539$

Gauge readings mm. of hg.		Diff.	Temp. deg. cent	Barometer	Pressure mm.	Test coils volts	Ratio $= \frac{\text{max.}}{\text{eff.}}$	Critical kilovolts max.	Critical intensity kv. cm.
288	1000	712	18.2	760	48	4.5	1.40	5.2	8.0
316	960	644	18.2	760	116	7.2	1.42	8.5	13.1
348	915	567	18.2	760	193	10.3	1.44	12.3	18.9
361	910	549	19.8	756	207	10.9	1.44	13.0	20.0
365	909	544	19.8	756	212	11.2	1.44	13.4	20.6
431	846	415	19.8	756	341	15.7	1.44	18.9	29.1
484	799	315	19.8	756	441	19.3	1.44	23.2	35.7
530	750	220	19.8	756	536	22.4	1.445	27.0	41.5
592	710	118	19.8	756	638	25.5	1.445	30.7	47.2
					756	29.3	1.445		
			19.8	756	756	29.5	1.445	35.5	54.6
					756	29.5			
					756	29.3			
755	597	158			914	34.0	1.445		
755	597	158			914	33.9			
754	597	157	19.8	756	913	34.0		41.0	63.1
754	597	157			913	33.9			
849	554	295			1051	38.2			
850	555	295	19.8	756	1051	38.2	1.445	46.0	70.8
850	555	295			1051	38.2			
850	555	295			1051	38.2			

tion is called to the accuracy with which observations may be repeated.

Empirical Formulas. As stated before, Peek has given the formula

$$g = 31\,\delta\left(1 + \frac{0.308}{\sqrt{\delta\, r}}\right)$$

connecting the critical intensity g in kilovolts per cm. with pressure, temperature and radius of conductor. Fig. 8 shows

curves for three sizes of conductor for the temperature 20 deg. cent. As indicated, the circles are observed points while the full lines are plotted from the formula given above. It is seen that as the formula stands, it does not meet our observations very closely, though it gives a curve of the correct general form. By suitable changes in the constants the formula is brought into close agreement.

Fig. 9 is plotted from the formula

$$g = 33.6\,\delta\left(1 + \frac{0.235}{\sqrt{\delta r}}\right) \tag{2}$$

The circles show the observed points as before. It is seen that with the formula so changed it represents the observations about

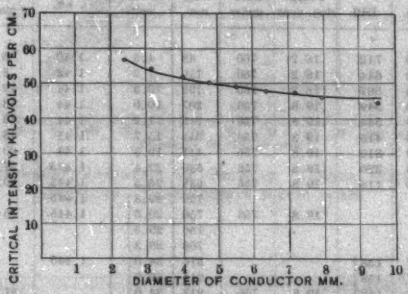


FIG. 7—VARIATION OF CRITICAL INTENSITY WITH SIZE OF CONDUCTOR AT 20 DEG. CENT. AND 76 CM. PRESSURE

as closely as the readings can be taken. This formula gives zero voltage for zero pressure provided r has a value greater than zero, which, of course, it has for any real case. As the present observations run only as low as 4 or 5 cm. pressure, they furnish no test on this point. Investigations are now under way to determine what becomes of the corona at very low pressures.

If in equation (2) the value of δ at 76 cm. pressure and temperature 20 deg. be substituted, the following formula is obtained:

$$g = 34 + \frac{11.2}{\sqrt{D}} \tag{3}$$

This formula gives the variation of critical intensity with D the diameter of conductor at standard temperature and pressure.

The curve in Fig. 7 is a plot from this equation, while the circles are observed points. In the earlier work a formula of the same form but with different constants was given, namely:

$$g = 32 + \frac{13.4}{\sqrt{D}} \qquad (4)$$

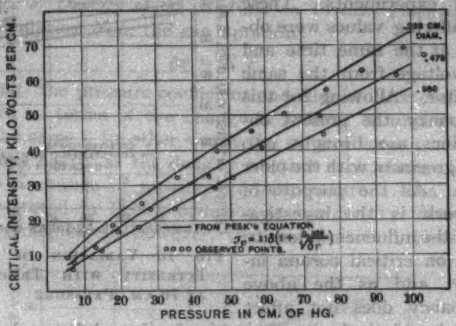


FIG. 8

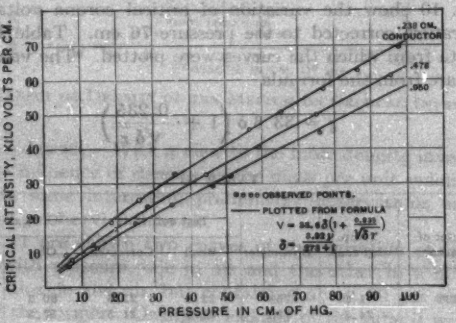


FIG. 9

The first constant of formula (4) is less than that of formula (3) while the second is greater, so the difference is largely one of curvature. What difference there is over the range of conductors observed is accounted for by a small discrepancy in the ratios of transformation of the transformers used in the earlier

experiments and in the present ones. It was found by trial in the earlier experiments that the indicated critical voltage with the 30,000-volt transformer with which those experiments were conducted was 54 kv. for a 0.345-cm. conductor and 52.4 for the 100,000-volt transformer which was used in the present set of experiments. These two differing values were obtained at the same time and with voltage from the same generator. Allowing for this discrepancy the present observations are brought into close agreement with the older values. As the purpose of this work is the investigation of the influence of density of gas on critical corona intensity, and as the above discrepancy does not affect the results relatively, its elimination has been left to a later date.

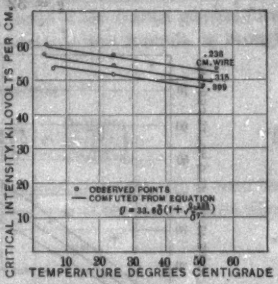


FIG. 10—VARIATION OF CRITICAL INTENSITY WITH TEMPERATURE AT 76 CM. PRESSURE

Variation of Critical Intensity with Temperature. The curves of Fig. 10 show the variation of critical corona voltage with temperature corrected to the pressure 76 cm. Table III gives the data from which the curves were plotted. The values computed are from the formula

$$g = 33.6\,\delta\left(1 + \frac{0.235}{\sqrt{\delta\, r}}\right)$$

TABLE III

Diameter of conductor	Temp. deg. cent.	Barometer	Test coil volts		Critical intensity	
			Read	Corrected	Obs.	Comp.
0.238	4.0	758	22.6	22.6	60.3	59.8
	24.3	760	21.5	21.5	57.5	56.6
	55.4	754	19.8	20.0	53.5	52.3
0.315	3.7	758	26.4	26.4	57.6	56.8
	24.2	760	25.0	25.0	54.3	53.4
	50.8	754	23.1	23.3	50.7	50.0
0.399	6.3	758	29.1	29.1	53.7	54.2
	24.2	760	28.1	28.1	51.8	51.3
	51.0	754	25.9	26.1	48.1	47.8

The diameter of tube used as outer conductor in these experiments was 10.5 cm. The curves in Fig. 9 are practically straight lines, as the range of temperature is not great enough to bring out any curvature. The agreenient with the revised Peek equation is also very close here.

Influence of Density of the Medium on Critical Intensity. A simple calculation from the gas equation

$$pv = RT$$

shows that the pressure coefficient and temperature coefficient interpreted in terms of the change in volume of unit mass of gas are the same. In other words the critical corona intensity in air varies nearly as the density whether such change is produced by a change of pressure or temperature. This idea is implicitly stated in Peek's equation in his density factor. It must be remembered, however, that his definition gives only

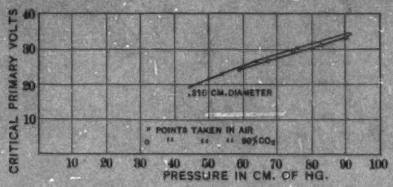


FIG. 11—EFFECT OF DENSITY OF THE MEDIUM ON CRITICAL INTENSITY

the relative density. With a view to the more definite investigation of the influence of density as the mass per unit volume we have made some interesting preliminary observations on the corona in a gas heavier than air.

In Fig. 11 are shown two curves of the variation of critical intensity with pressure, one in air and the other in a mixture of carbon dioxide and air, but containing about 90 per cent by volume of the former. Owing to leakage of the tube it was not possible to fill it with the pure gas. It is seen that there is little change due to the presence of the carbon dioxide, although its density is about 1.5 times that of air. It appears, then, from these experiments, that the variation of critical intensity does not, in fact, depend on the density, but is rather a function of the separation of the molecules of the gas, since according to the law of Avogadro the number of molecules in a given volume of gas is a

function of the pressure and temperature only, and does not depend on the nature of the substance. The indication from these curves then is that the relation of the electric intensity and corona formation is found in the average separation of the molecules. This is in fact a principal tenet of the theory of secondary ionization or ionization by collision as explaining all forms of spark discharge in gases. The opinion has been expressed in several places in this series of papers that the theory of second-

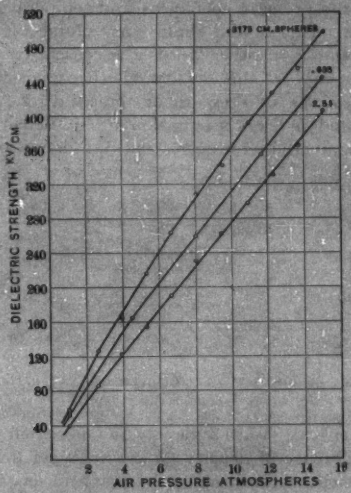


FIG. 12—SPARKING POTENTIALS BETWEEN SPHERES, BY WATSON

ary ionization offers the most promising explanation of corona formation.

IV. COMPARISON WITH RESULTS ON SPARKING POTENTIALS

Fig. 12 is reproduced from a paper by Watson on "The Dielectric Strength of Air."[6] The curves show the variation of the sparking potentials between spheres with variation of pressure. The pressures range from atmospheric upward, so that

6. *Jour. Inst. Elec. Engrs.*, Vol. XLIII, 1909.

they are not directly comparable with the pressures in the present set of corona experiments. From the work of other observers, however, it is known that the curves extend down toward the zero until they reach the so-called "critical pressure." Upon further reduction of pressure the curves turn sharply upward. These critical pressures vary with the length of spark gap, ranging from 3 to 0.3 mm. for spark gaps of 1 to 10 mm., respectively.[7]

It is seen by reference to the curves that their general shape is the same as for critical corona intensity. The chief question of interest in both cases is the departure from the linear law as the curvature is probably due to a common cause. By analogy with curves for sparking potentials it may be anticipated that the critical corona intensity may rise at very low pressures. It is well known that it is difficult to get the vacuum tube discharge at very high vacua.

The results obtained with corona in carbon dioxide were to be anticipated from Paschen's law. This law states that the sparking potential depends on the product of the pressure and the spark length. Curves plotted with products of pressure and spark length as abscissas and sparking potentials as ordinates are nearly the same for air and carbon dioxide but differ considerably for hydrogen. No attempt was made to try hydrogen as the medium surrounding the conductor in the present set of experiments owing to the presence of some leakage of the tube which might have resulted in the production of an explosive mixture. We wish to emphasize the simplicity of the corona apparatus as a method for studying the theory of gaseous conduction.

V. Discussion

As most of the observed laws of corona formation are in accord with the theory of ionization by collision, a brief statement of some of the fundamental experiments and conclusions of that theory will not be out of place.

When two parallel conducting plates are connected to a source of potential difference and the gas between them ionized by X-rays or radium, it is found that a current passes. This current increases at first as the potential difference is increased, but later attains a stationary value. No further increase of the current with increasing voltage is noted until a considerably higher voltage is reached when the current again increases rapidly with increasing voltage. The interpretation of this phenomenon is

7. "Conduction of Electricity through Gases," J. J. Thomson, 1906.

that the X-rays produce ions at a definite rate so that the current which can be produced by sweeping out all these ions has a limit. The stationary value of the current spoken of, marks this limit. When, however, the voltage becomes sufficiently high the ions attain a velocity which enables them to produce new ones by collision with neutral atoms. This is known as ionization by collision or secondary ionization. This theory of ionization by collision accounts for the order of magnitude of the critical corona voltage which in the limiting case of plane surfaces is approximately 30 kv. per cm. The mean free path of the electrons is about 6×10^{-5} cm. at 76 cm. pressure and 20 deg. cent., as has been shown by Townsend and others. This is about six times the mean free path of the molecules of the gas. For the ordinary sizes of conductors the voltage over a mean free path of an electron is about 2 volts. This indicates that the critical intensity is that which gives the ionizing voltage of about 10 volts[8] in a distance of five times the mean free path, or in other words some of the electrons having a free path of five or more times the average, start the corona.

The ionization theory fails as yet to show why the critical intensity varies with the size of conductor and why the variation of critical intensity with pressure does not follow a linear law. As has been frequently shown, the critical intensity rises quite rapidly as the size of conductor is reduced. The intensity in the gas falls away as $1/r$ where r is the distance from the center of the conductor, and from this it is seen that the intensity diminishes much more rapidly in the immediate neighborhood of a small conductor than a large one. Nevertheless, the diminution in a distance of five or ten mean free paths of an electron is negligibly small in any practical case.

The corona begins and ends at approximately the same voltage on the e.m.f. wave. This indicates that the rate of recombination of the ions is very great. It appears possible from this fact that the corona will not start until the intensity is high enough over some depth such as half a mm. on account of the great amount of recombination which goes on in the neighboring space, where the intensity is too low.

VI. Conclusions

1. The critical corona-forming electric intensity in air has been determined over the range of pressure from 5 cm. to 108 cm.

8. Bishop: *Physical Review*, Vol. XXXIII, 1911.

of mercury, for nine sizes of round conductor of diameters from 0.23 to 0.95 cm.

2. A few observations on the influence of temperature within the range of 5 deg. to 55 deg. cent. are also recorded.

3. The results are in substantial agreement with the empirical relation between electric intensity, pressure and temperature suggested by Peek.

4. Experiments with carbon dioxide indicate that the critical corona intensity is independent of the absolute density of the gas, but depends on the number and spacing of the molecules, in accord with the theory of secondary ionization.

BIBLIOGRAPHY

Steinmetz: *Dielectric Strength of Air*, TRANS. A. I. E. E., Vol. XV, 1898

Scott: *High Voltage Power Transmission*, TRANS. A. I. E. E., Vol. XV, 1898.

Ryan: *Conductivity of Atmosphere at High Voltages*, TRANS. A. I. E. E., Vol. XXIII, 1904.

Mershon: *High Voltage Measurements at Niagara*, TRANS. A. I. E. E., Vol. XXVII, 1908.

Balch: "80,000-Volt Transmission Line," *Jour. of Elec.*, 1904.

Brecht: "A 500,000-Volt Experimental Line," *Electrotechn. Anzeiger*, Vol. XXVI, 1909.

Lyndon: "The Corona and Design of High Tension Lines," *Elec. Review and Western Electn.*, Vol. LIV, 1909.

Watson: "Atmospheric Loss under Continuous Current," *Electrician*, September 3, 1909; February 11, 18, 1910.

"Dielectric Strength of Compressed Air," *Jour. Inst. Elec. Engr.*, Vol. XLIII, 1909.

Moody and Faccioli: *Experiments on Corona*, TRANS. A. I. E. E., Vol. XXVIII, 1909.

Kemp and Stephens: "Disruptive Voltage in Air," *Inst. Elec. Engr.*, Vol. XLIV, 1910.

Hayden and Steinmetz: *Disruptive Strength of Air*, TRANS. A. I. E. E., Vol. XXIX, 1910.

Whitehead: *The Electric Strength of Air, I, II, III*, TRANS. A. I. E. E., 1910, 1911, 1912.

Peek: *The Law of Corona and the Dielectric Strength of Air, I and II*, TRANS. A. I. E. E., 1911, 1912.

"The Nature of Corona," *G. E. Review*, December, 1912.

Görges, Weidig and Jaensch: "Experiments on Corona Loss," *Electrotechn. Zeitschr.*, 32, 1911.

Wecker: "Sparking Pressure under Commercial Conditions," *Zeitschr. Verins. Deutsch. Eng.*, 55, 1911.

West: *High Voltage Line Loss Tests*, TRANS. A.I.E.E., Vol. XXX, 1911.

Faccioli: *Tests of Losses on High Tension Lines*, TRANS. A. I. E. E., 1911.

Zickler: "Zur Berechnung der Koronaverluste," *Electrotechn. und Maschinenbau*, September 15, 1912.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N. Y., June 27, 1913.

Copyright, 1913, By A. I. E. E.

THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION

BY W. W. STRONG

Purpose and Experimental Apparatus

The purpose of the present investigation was to obtain the watt-voltage curves of corona discharge under certain conditions that are met in the process of precipitating fumes, dust and smoke electrically. Up to the present time the engineer has been mostly interested in the energy losses that occur on high-voltage transmission lines. In general this corona current is an alternating one taking place at comparatively low voltages. In the electrical method used to remove suspended dust, smoke and fumes from gases it is advantageous to use a unidirectional corona current at as high potentials as possible without sparking or arcing taking place. On high-voltage transmission lines the aim is to prevent corona discharge. In electrical precipitation the aim is to produce as copious a corona current as possible.

In the present work[1] the apparatus is that indicated in outline in Fig. 1. The transformer T (ratio of transformation 237) is supplied by 220-volt mains through a lamp resistance LR. A is an ammeter, V a voltmeter and W a precision wattmeter.

The transformer high-voltage terminals are connected to a rectifier R consisting of a commutator of an angular width of 30 deg. run at 1800 rev. per min. by a synchronous motor, the primary current being 60-cycle. This makes the effective angle of the commutator 60 deg. The rectifier apparatus was made so that the synchronous motor frame could be revolved through 100 deg. and clamped in any position while running at full speed.

1. See *Journ. Frank. Inst.*, Sept., 1912.

The position of the motor was read as being at 0 deg. when the motor frame was in a vertical position. When on open circuit the position of the motor for minimum sparking on the rectified side was 36 deg. from the vertical. The corona discharge takes place between the wire electrode *A E* and the grounded cylinder *C*. *B* is a blower for producing air currents in *C*. *G* is a furnace heated by natural gas or by coal. By using natural gas the air can be heated so that at *A E* its temperature may be 300 deg. cent. This "hot air" contains a large percentage of CO_2 and is in a state of greater or less ionization.

An illustration showing one of the precipitation chambers used in the present investigation is indicated in Fig. 2 in vertical section, and was designed by Prof. Nesbit and the writer. 11 and 12 are inlets for gases; *A E* is the active electrode and usually consisted of No. 20 wire; headers 13 and 14 serve to give rigidity to the five-inch cylinders 15; the cylinders are arranged in concentric circular series and in this chamber numbered 25, being 4 ft. (1.2 m.) in length; the header is made to fit tightly over the deposition box 10; 1 and 2 are large insulators connected by a rod 3, and to spoked rings 4 and 5 to which are fingers 6, and set screws 7 for centering and keeping the active electrodes stretched; 8 and 9 are supporting pieces that permit the whole system of electrodes to be raised off the settling chamber.

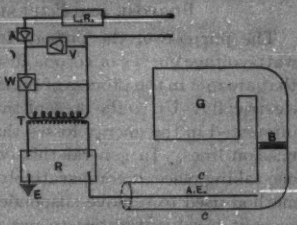


Fig. 1—Diagram of Apparatus and Connections

When wires are used as active electrodes within metallic cylinders they are frequently set into vibration, a corona discharge taking place from the wire. This vibration is quite marked when the wire is not axially fastened and when the difference of electrical potential is almost equal to the sparking potential. The vibrations are much more easily excited and are much more violent when the corona is positive. This is to be expected, since the positive corona is very greatly affected by non-uniformity of the electric field. The positive corona brush discharge is entirely localized in the more intense portions of the electric field. On the other hand, the visible negative corona does not spread very far from the active electrode surface and is not easily modified

by the active electrode not being axially placed within the cylinder. This is one of the reasons why a negative corona is usually more effective in electrical precipitation than the positive corona.

The Nature of the Corona Discharge

It must be remembered that the corona discharge is only a special form of electrical discharge and is closely related to the point discharge, the various vacuum tube discharges, oscillatory and brush discharges, arcs, etc. Aubertin,[2] by using certain conditions of discharge, has observed the characteristic bright and dark regions in discharges at ordinary pressures by using a microscope. It is unfortunate that no study of the corona discharge has been made through a wide range of pressures, and it is quite possible that such a study would indicate the presence of an anode and cathode glow in the positive and negative coronas respectively. Such a glow or region of intense ionization would probably explain the fact that the break-down strength of air is greater for smaller wires, since the secondary ionization may take place in the gas near the metallic surface rather than at the metallic surface itself.

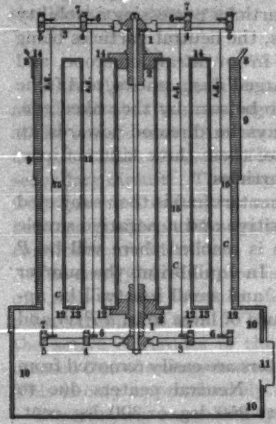


Fig. 2—Vertical Section through Precipitation Chamber

The ions produced by the corona discharge in pure gases such as oxygen and nitrogen possess a mobility of about a centimeter per second, the negative ions usually having a slightly greater mobility. There are many conditions, however, where ions have a much smaller mobility of about a thousandth part of that of "small" ions. Such ions are produced when hydrochloric acid acts on zinc, marble, etc.; when oxygen is prepared by heating potassium permanganate; when combustion takes place in flames, the burning of coal, etc. The presence of dust, fume particles, smoke,

2. C. R., 154, p. 874, 1912.

mist, vapor sprays, etc., results in ions of large mobility combining with these particles and forming ions of very small mobility. These ions may have as small a mobility as 0.0002 cm. per second or less, and will be called "large" ions. Large ions existing in the immediate neighborhood of flames have a diameter of about 0.1 μ (particles containing say 10^6 molecules), and exist in large numbers in free air (about 16,000 per cu. cm. under ordinary conditions).

The charged particles that one finds in hot gases, fumes, smoke, etc., consist of "simple" ions similar to those found in pure gases; "large" ions consisting of charged particles possessing a mobility of about 0.0001 cm. per sec. or less, the neutral particles being very small, usually invisible except in an ultramicroscope, and often called neutral centers; and charged dust, smoke, and fume particles of a size sufficiently large to be seen by the naked eye. In any gas the conditions will always be directed towards an equilibrium in the relative numbers of these three kinds of ions, the neutral centers and the dust particles.

Suppose a gas contains M neutral centers and is then subjected to an ionizing agent producing p positive and n negative simple ions per second. When equilibrium is reached there will be P positive and N negative large ions. In equilibrium the number of recombinations of neutral centers and small ions will be approximately equal to the disappearance of large ions, $d\,P/dt$ and dN/dt.

Broglie has shown that neutral centers are easily removed from gases by filtration through cotton. Neutral centers due to water dust are destroyed by heating to 250 deg. or 300 deg. cent. The ratio $P + N/M$ is very small. Broglie has succeeded in charging netural centers by the action of an electric field under certain conditions. Large ions often have a charge from 30 to 50 times as great as that of the elementary charge.

In electrical precipitation the presence of the simple and large ions has a very great effect upon the sparking and arcing potential. Some of the following data show this very clearly. For the most effective precipitation it is best to operate as near the sparking potential as possible. When a large amount of suspended matter is present in the gas the sparking potential is approximately the same as in air. An example illustrating this is the sparking potential between electrodes maintained at a constant difference of potential.

(Gap condition)		(Minimum spark gap length)
Room air		28 mm. gap length.
Flue gas	35 deg. cent.	35 " " "
" "	60 " "	35 " " "
" "	90 " "	37 " " "
" "	95 " "	45 " " "
Dense smoke	95 " "	30 " " "

The alternating corona is to be explained as depending on the properties of the positive and negative coronas. The positive and negative coronas are secondary ionization phenomena and may be influenced by the nature of the ions existing before the discharge commences.

Positive Current Corona Losses

In the data on positive and negative coronas it must be remembered that the reading instruments are on the primary side of the transformer; that about 60 deg. of the wave form is rectified; and that there are four small spark gaps in series in the secondary circuit. The length of these spark gaps was generally from one to about three mm. When any comparison is made between positive and negative corona the electrical and rectifier conditions are identical.

The energy consumption is measured at different voltages when one high-voltage terminal of the transformer is grounded and the other terminal is open. The open terminal is then connected to the active electrodes of the precipitation chamber and the increased loss of energy is assumed to go into the corona discharge. This is only approximately true.

Experiments have been performed for only a small range of gas velocity changes. In the experiments recorded in Table I a lamp resistance was placed in the primary of the transformer, lamps being gradually added in parallel in (*a*) and decreased in (*c*). In the case of the positive corona, the production of a draft did not increase the spark potential difference of the corona loss to any appreciable extent. This result is shown in the last reading of (*a*) and the reading of (*b*). In other words, the character of the discharge was but slightly changed by putting the air into motion.

The introduction of hot furnace gases causes a very considerable decrease in the sparking potential. In this instance the sparking potential was reduced from 30,600 to 28,500 volts. The sparks were of the "snapping" oscillatory type. The

number of lamps in the readings (1), (2), (3), (4), and (5) was the same. Readings (5) to (9) were made at practically the same potential, the amount of sparking decreasing. The sparks taking place at (5) consume almost as much energy as the corona itself. The positive corona loss appears to be slightly less in the hot gases than in room air. The energy loss due to the corona discharge and the transformer losses are given as "total." The

TABLE I

POSITIVE CORONA (ROTOR VERTICAL)

(a) Still air at room temperature.		Watts loss	
Secondary voltage	Primary amperes	Total	Corona
8,800	0.55	12	—
21,300	0.95	76	10
23,800	1.45	128	52
24,000	1.94	182	105 (?)
27,500	2.42	236	142
28,700	2.95	285	185
29,300	3.4	330	225
30,200	4.2	410	300
30,400 (1)	4.7	448	345
30,200 (2)	4.7	447	345
(b) Air velocity about 800 cu. ft. per min. Room temperature			
30,600 (3)	4.7	447	342
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
29,500 (4)	5.1 sparking	425	315
28,000 (5)	5.2 "	416	316
28,500 (6)	4.6 "	386	266
28,300 (7)	4.2 "	350	239
28,500 (8)	3.6 "	324	204
28,500 (9)	2.9 "	273	153
27,600	2.4	232	137
26,000	1.96	181	94
24,300	1.46	130	46
21,000	0.95	73	8

"total" loss minus the loss in the transformer and rectifier on open circuit (one terminal grounded) is given as the corona loss for 100 ft. (30.4 m.) of No. 20 wire in 5-in. (12.7-cm.) cylinders. The wires were cleaned only to the extent of careful brushing. The voltage is the effective volt reading of the primary multiplied by the ratio of transformation. The readings are of relative value only as the electromotive force wave is distorted from the sine form by the action of the rectifier.

Negative Current Corona Losses

From Tables I and III, which give comparable results for positive and negative corona, it will be seen that the ionization of a gas affects the two coronas differently. It was hoped that the properties of the alternating corona could be shown to be the additive effect (wattage loss curves, sparking potential, etc.) of the positive and negative coronas. On account of the irregularities introduced by the present form of rectifier this could not be

TABLE II

Positive Corona (Rotor 15 deg. from Vertical)

(a) Still air at room temperature		Watts loss	
Secondary voltage	Primary amperes	Total	Corona
21,800	1.0	79	—
27,300	1.42	129	35
31,000	1.8	178	63
33,500	2.23	220	85
34,600	2.63	257	115
36,300	3.0	293	130
36,800	3.4	319	150
37,200	3.55	345	165
38,000	5.0	388	198
(b) Air velocity about 800 cu. ft. per min. Room temperature			
38,600	4.5	400	200
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
36,500	4.6	360	195
36,300	4.15	337	166
36,000	3.6	319	160
35,600	3.1	290	135
35,000	2.65	253	103
33 200	2.25	219	80
30,700	1.85	178	63
27,200	1.4	130	35

done. A new form of rectifier is being devised to eliminate these effects as much as possible.

The following Table III gives the loss wattage due to a negative corona, the position of the rotor and the rectifier electrodes being the same as was the case when the data in Table I were taken. It is assumed that the fall in potential across the rectifier electrodes is the same as in the case of the positive corona. For given differences of potential the negative corona loss is less than the positive corona loss. In still air the sparking potential

is approximately the same for both coronas. The existence of a comparatively small air velocity permits the potential difference to be raised very considerably as is shown in (*b*).

The sparking potential difference for the hot furnace gas is about 4000 volts less than the value for air. Above 30,000 volts, the corona loss appears to be slightly greater in air than in the furnace gas.

Within the range of values used in these experiments it was found that the existence of a draft of air did not affect the wattage loss or the sparking potential of the positive coronas to any appreciable extent. The sparking potential is slightly greater when the air is in motion. The existence of even a small air

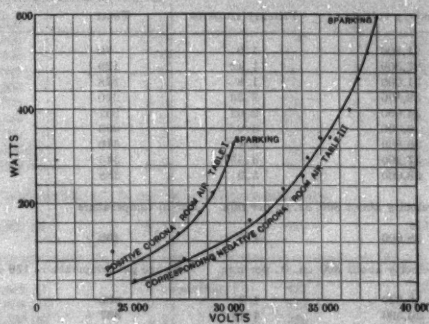


FIG 3—WATTS LOSS—ELECTRODES OF FIG. 2

velocity results in a very decided increase in the sparking potential of the negative corona. This results in the possibility of a much greater corona current density being obtainable in the process of precipitation when the active electrode is made negative. When warm ionized air is passed through the negative corona discharge the sparking potential is greatly reduced, the reduction in some instances being to the same or less value than that for still room air.

Assuming that the potential drop across the rectifier gaps is independent of the direction of flow of the current, it follows that for corresponding voltages the loss due to the positive corona is greater than that due to the negative.

High-Voltage Current Electrolysis

Some measurements were made of the electrolytic gas produced by the corona currents. The values obtained agreed approximately with the energy loss measurements. Alternating current corona begins to produce electrolysis when the voltage becomes

TABLE III

Negative Corona (Rotor Vertical)

Secondary voltage	Primary amperes	Watts Total	Watts Corona
(a) Still air at room temperature.			
8,800	0.5	12	
21,600	0.95	76	8
25,300	1.38	130	45
27,800	1.8	184	85
29,700	2.2	234	125
31,200	2.58	281	165
32,500	2.87	325	198
33,000	3.2	364	234
34,000	3.47	400	260
34,300	3.7	440	298
35,000	4.1	484	334 Occasional sparking.
(b) Air velocity about 800 cu. ft. per min. Room temperature.			
35,500	4.0	476	326
36,600	4.5	568	403
37,000	5.1	643	468
37,500	5.5	706	526
38,000	5.7	780	590 Sparking
(c) Air velocity about 800 cu. ft. per min. Furnace gas temperature 170 deg. cent.			
35,000	5.0	573	392 Occasional sparking
34,000	4.35	492	352
33,300	3.65	411	280
32,500	3.35	377	251
31,600	3.1	333	213
30,800	2.7	291	186
29,300	2.3	238	130
27,300	1.88	186	91
24,700	1.33	130	50
21,300	1.0	78	10

sufficiently high or when short spark gaps are introduced into the circuit. Efforts are being made to make useful applications of these facts.

Summary

1. Since the negative corona is much more uniformly distributed about the active electrode, and on account of its greater

stability as regards sparking, the negative corona discharge is much more suitable than the positive for electrical precipitation. In the precipitation chamber described (capable of cleaning about 800 cu. ft. (22.6 cu. m.) of gas per min.) the negative corona consumes about 300 watts under the best conditions for precipitation.

2. Under similar conditions of the electrical circuit the loss due to the positive corona is slightly greater than that due to the negative corona at the same voltage.

3. For values of the electric field near the sparking potential the negative corona watt loss curve is flatter than the curve for the positive corona.

4. The positive corona loss in room air and ionized furnace gases is about the same. Increasing the air velocity affects the sparking potential and the corona loss but slightly.

5. Increasing the air velocity increases the sparking potential of a negative corona in ordinary air. The corona watt loss is considerably greater in hot ionized gas than in air.

6. The positive corona tends to go over to an oscillatory spark while the negative corona is more easily changed into an arc form of discharge.

7. Since the negative corona curve is the flatter and since larger negative corona currents can be obtained, the negative corona is much better adapted for electrical precipitation than the positive corona.

8. The presence of suspended matter in the gases does not affect the corona currents greatly.

9. The greater "dielectric strength" of air near small wires may be due to the corona discharge containing a "glow" region near the wire.

10. The presence of suspended matter in hot gases increases the sparking potential in these gases. This is probably due in part to the disappearance of the smaller ions. The presence of suspended matter in ordinary air decreases the sparking potential.

Application to a Smoke and Fume Indicator

Many of the effects of the presence of dust and smoke upon the high-tension electrical discharges are illustrated in the action of the smoke indicator. This instrument throws in an indicating circuit (such as a bell or red light circuit) whenever the smoke or fumes in a gas exceed a certain density. It consists of a high-voltage small-wattage (about 100 watts) transformer

in whose high-tension circuit are included a set of parallel spark gaps, one set of electrodes being placed in the flue gases and the other set being placed in air. The circuit conditions in the transformer are such that the discharge between the air electrodes is oscillatory and can be made to throw in circuits by the use of wireless telegraph methods.

The presence of dust, smoke and fumes increases the sparking potential of the flue gases so that when the intensity of this suspended matter exceeds a certain value, sparking takes place between the air electrodes. By regulating the length of the spark gaps the indicator circuit can be thrown on whenever the smoke density exceeds any given value.

In the absence of smoke, ordinary furnace gases permit the passage of a quiet violet flame discharge. These flames are ribbon-like and are forked. Under these conditions, the discharge is a maximum and the potential a minimum. As the amount of suspended matter is increased, this violet discharge gradually disappears, the current decreases and the potential increases. When the smoke is very dense the discharge becomes practically the same as in a non-ionized gas.

The explanation of this whole phenomenon is probably due to the ions produced in the furnace combining with the dust particles.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

Copyright, 1913. By A. I. E. E.

LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR—III

(A Theory of Rupture)

BY F. W. PEEK, JR.

Visual Corona and Rupturing Energy

The apparently greater strength of air around small conductors was long attributed to a film of condensed air at the conductor surface having a greater relative effect for small conductors than large ones.

In *The Law of Corona—I**, as the result of extensive experiments it was shown that at atmospheric pressure (76 cm. barometer—25 deg. cent.) the maximum gradient at the surface of the wire when visual corona starts could be expressed by the equation

$$g_v = g_0\left(1 + \frac{0.301}{\sqrt{r}}\right) = 29.8\left(1 + \frac{0.301}{\sqrt{r}}\right) \qquad (1)$$

The mathematical expression for the gradient at x cm. from the conductor surface is, where x is small,

$$g = \frac{e}{(r + x)\log_e s/r} \qquad (2)$$

Then if $e = e_v$, the voltage at which visual corona starts, and $x = o$,

$$g_v = \frac{e_v}{r\log_e s/r} \qquad (3)$$

*Trans. A. I. E. E., Vol. XXX, 1911, p. 1889.

Equating (1) and (3)

$$g_0\left(1+\frac{0.301}{\sqrt{r}}\right)=\frac{e_v}{r\log_e s/r}$$

or

$$g_0=\frac{e_v}{(r+0.301\sqrt{r})\log_e s/r}=29.8 \qquad (4)$$

From (2) it can be seen that g_0 is the gradient $0.301\sqrt{r}$ cm. from the conductor surface. This means that when corona starts, the *gradient* $0.301\sqrt{r}$ *cm. from the conductor surface is always constant*, g_0, independent of the size of the conductor or the spacing. See Fig. 1.

The theory advanced* for this *apparent* variation of the strength of air was:

Air has a constant strength g_0 for a given density, but a finite amount of energy is necessary to cause rupture or start corona. Hence rupture starts, not when the gradient is g_0 at the surface of the conductor, but only when the gradient is g_0 a finite distance from the surface; that is, the stress at the conductor surface must exceed the elastic limit g_0, or be increased to g_v in order to supply the necessary rupturing energy between the conductor surface and a finite distance in space ($0.301\sqrt{r}$ cm.) away where the stress is g_0 and breakdown occurs. The energy stored in this space may be called the rupturing energy. See Fig. 1.

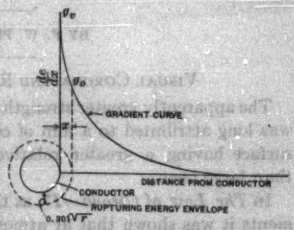


FIG. 1

Air Density. If g_0 is the strength of air at the standard density $\delta = 1$ (76 cm. – 25 deg. cent.), the strength at any other relative density should be

$$\delta\, g_0$$

where

$$\delta=\frac{3.92\,b}{273+t}$$

Law of Corona and Dielectric Strength of Air—I, Trans. A. I. E. E. Vol. XXX, p. 1889.

The energy distance $a = 0.301\sqrt{r}$ should also vary with δ if the rupturing theory given above holds, or

$$a = 0.301\sqrt{r}\,\phi(\delta)$$

Then g_v should be written

$$g_v = g_0\,\delta\left(1 + \frac{0.301}{\phi(\delta)^*\sqrt{r}}\right)$$

This was shown to be the case in the *Law of Corona*—II,* or that

$$g_v = 31\,\delta\left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \text{ kv. per cm.} \qquad (5)$$

therefore

$$a = 0.301\sqrt{r/\delta}$$

It was also shown at this time that the effect was the same whether δ was varied by change of temperature or change of

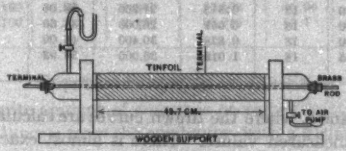


FIG. 2

pressure. The range of δ in these experiments was from 0.6 to 1.2, between which limits the curve between δ and g_v, though over the natural range of δ, is still very nearly a straight line. From (5), the form of which was predicted from theory, the curve shows a decided bend to $\delta = 0$ at the low values of δ.

Experiments were later made over the wide range of $\delta = 0.02$ to $\delta = 1$ in order to check equation (5) over this range as an additional check on the energy theory. The visual corona point was measured on polished brass rods in the center of a metal-lined glass cylinder. See Fig. 2.

The diameter of the cylinder was 7.36 cm., while the rod diameters ranged from 0.15 to 0.5 cm. In making observations the air was exhausted from the tube until the desired pressure was reached; voltage was then applied and increased until the starting point of corona was reached. The tube was "aired" out before

Law of Corona and Dielectric Strength of Air—II, TRANS. A. I. E. E., Vol. XXXI, 1912, p. 1051.

each reading. Some of the results of experiments, together with values calculated from the equation (5) given last year, are found in Tables I, II, and III. The results are shown graphically

TABLE I

DIAMETER OF BRASS ROD = 0.508 CM. = 0.2 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	δ $\frac{3.92\,b}{273+t}$	$g_v = \frac{e_v}{r\,(\log_e R/r)}$	g_v max. measured	g_v max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta r}}\right)$ kv. per cm.
1.7	1.392	23	0.0225	2,046	2.894	3.47
5.6	3,150	24	0.074	4,620	6.54	7.33
5.85	3,720	18	0.0788	5,460	7.72	7.63
8.8	4,610	24	0.116	6,780	9.60	9.90
13.5	6,580	18	0.182	9,660	13.68	13.55
16.0	7,470	18	0.216	10,960	15.50	15.27
28.2	11,390	18	0.38	16,740	23.66	23.2
38.1	14,470	18	0.513	21,260	30.06	29.1
49.5	17,700	18	0.667	26,000	38.60	35.75
61.5	20,700	18	0.828	30,400	43.00	42.7
75.7	24,535	18	1.019	36,000	50.92	50.25

in Figs. 3, 4 and 5, where the drawn curves are calculated, and the points are measured values. There is almost exact agreement throughout the range; any variation from the curve seems rather to be due to experimental error in reading pressure.

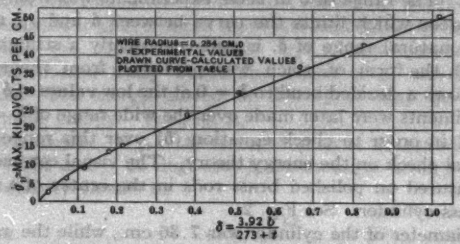


FIG. 3—CORONA AT LOW AIR DENSITIES

It is interesting to note that with two polished wires and the aid of the equation

$$*e_v = g_0\,\delta\,r\left(1+\frac{0.301}{\sqrt{\delta r}}\right)\log_e s/r$$

voltages anywhere may be measured by varying the spacing until corona starts and solving for e_v at this spacing.

TABLE II

DIAMETER OF BRASS ROD = 0.381 CM. = 0.150 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	δ $\frac{3.92\,b}{273+t}$	$g_v = \frac{e_v}{r\,(\log_e R/r)}$	g_v max. measured	g_v max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta r}}\right)$ kv. per cm.
5.33	2,880	27	0.0697	5,080	7.19	7.8
10.7	4,580	24	0.1412	8,090	11.45	12.40
11.2	4,920	27	0.1463	8,680	12.28	12.15
19.3	7,400	27	0.252	13,060	18.47	18.58
27.7	9,550	27	0.362	16,870	23.85	24.06
36.6	12,000	27	0.478	21,200	30.00	29.60
46.4	14,450	25	0.6125	25,500	36.07	35.70
47.0	14,600	27	0.614	25,800	36.50	35.80
53.7	16,300	27	0.728	28,800	40.75	40.75
60.6	17,760	25.5	0.792	31,350	44.30	43.5
66.0	18,400	27	0.867	32,500	46.00	46.75
75.0	21,100	25	0.997	37,250	52.7	52.25

ELECTRIC STRENGTH OF AIR FILMS

If a definite amount of energy is necessary to start rupture at a finite distance a from the conductor, with a surface gradient g_v,

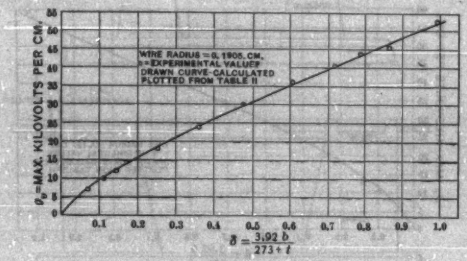


FIG. 4—CORONA AT LOW AIR DENSITIES

it is interesting to speculate what will happen at very small spacings or when the distance between conductor surfaces is of the order of a. See Fig. 6.

Law of Corona and Dielectric Strength of Air—II. TRANS. A.I.E.E., Vol. XXXI, 1912, p. 1051.

As the free "energy storage" or "accelerating distance" is limited, a greater force or gradient should be required, provided the energy theory is true, when the distance between the conductors

TABLE III

DIAMETER OF BRASS ROD = 0.254 CM. = 0.1 IN. (IN 7.36-CM. GLASS TUBE COVERED WITH TIN FOIL)

Pres. abs. cm.hg.	Volts read	Temp. deg. cent.	δ $\frac{3.92\,b}{273+t}$	$\mathcal{E}_y = \frac{e_y}{r\,(\log_e R/r)}$	$\mathcal{E}_y$ max. measured	$\mathcal{E}_y$ max. calculated $31\,\delta\left(1+\frac{0.301}{\sqrt{\delta r}}\right)$ kv. per cm.
4.9	2,490	22	0.0651	5,800	8.20	8.81
7.4	3,175	21	0.0987	7,400	10.45	11.27
10.3	3,925	21	0.1373	9,150	12.93	13.96
23.7	7,500	21	0.316	17,470	24.70	24.54
38.0	10,600	21	0.507	24,700	34.90	34.40
49.9	13,100	20.5	0.666	30,530	43.20	42.00
62.75	15,550	20.5	0.838	36,260	51.30	50.00
76.5	18,000	20.0	1.023	42,000	59.45	58.25

approaches a (see Fig. 6 (b) and (c)). Experiments were made to determine this, using spheres as electrodes. The ideal electrodes for this purpose would be concentric cylinders, but the use of these, as well as parallel wires, at small spacing seemed impracticable.

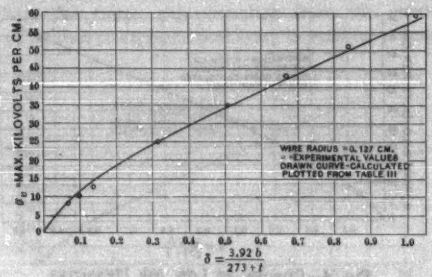


FIG. 5—CORONA AT LOW AIR DENSITIES

Spark-over and corona curves were made on spheres ranging in diameter from 0.3 cm. to 50 cm. and spacings from 0.0025 cm. to 50 cm. This discussion applies only to spacings up to $2R$ where corona can not yet form.

In these tests a 60-cycle sine-wave voltage was used. For the small spacing, the spheres were placed in a very rigid stand. One shank was threaded with a fine thread, the other was non-adjustable. In making a setting the adjustable shank was screwed in until the sphere surfaces just touched, as indicated by completing the circuit of electric bell and single cell of dry battery. A pointer at the end of the shank was then locked in place, after which the shank was screwed out any given number of turns or fraction of turns, as indicated on the stationary dial. For larger spacings other stands were used. Care was taken that surrounding objects were far removed from the spheres, to prevent distortion of the field.

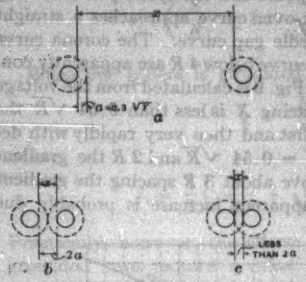


FIG. 6

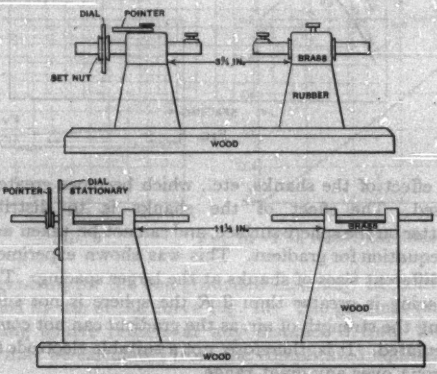


FIG. 7—SPECIAL SPARK-GAP STANDS FOR SPHERES

A typical spark-over-spacing curve, and corona-spacing curve, is shown in Fig. 8. Theoretically, up to a spacing of 2 R, corona cannot form and spark-over must be the first evidence

of stress, or, in other words, corona and spark-over are the same. Practically, corona cannot be detected until a spacing of 8 R is reached. This is because up to this point the difference between the corona starting point and the spark point is very small. Above 8 R the spark-over curve approaches a straight line, as in the case of the needle gap curve. The corona curve above 4 R and the spark-over curve below 4 R are apparently continuous. The gradient curve Fig. 9 is calculated from the voltage curve Fig. 8. Where the spacing X is less than $0.54\sqrt{R}$ the gradient increases slowly at at first and then very rapidly with decreasing spacing. Between $X = 0.54\sqrt{R}$ and 2 R the gradient is very nearly constant. Above about 3 R spacing the gradient apparently increases. This apparent increase is probably due

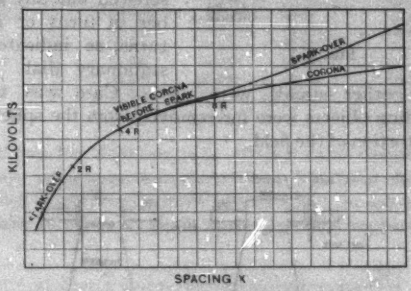


FIG. 8

to the effect of the shanks, etc., which becomes greater as X is increased. The effect of the shanks is to distribute the flux better on the sphere surface, and can not be taken account of in the equation for gradient. This was shown experimentally by using different sizes of shanks at the larger spacing. Thus when the spacing is greater than 3 R the sphere is not suitable for studying the strength of air, as the gradient can not conveniently be calculated. It is, therefore, not a suitable electrode for studying corona over any great range.

The maximum gradient at the surface of a sphere, (non-grounded), may be calculated from the equation

$$g = \frac{E}{X} f \tag{6}$$

Where X is the spacing between the nearest surfaces of the spheres, and E the voltage

$$f = 1/4\left(\frac{X}{R} + 1 + \sqrt{\left(\frac{X}{R} + 1\right)^2 + 8}\right)^*$$

When one sphere is grounded the gradient is theoretically:

$$g = \frac{E}{X} f_1$$

where

$$f_1 = \frac{1}{2}\left\{\frac{X}{R} + \sqrt{\left(\frac{X}{R}\right)^2 + 4}\right\}$$

Practically, however, the effects of the shanks, etc., for the grounded case require a value f_0 which we have determined experimentally. The case of one sphere grounded is not considered here.

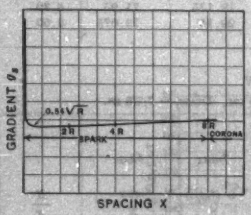


FIG. 9

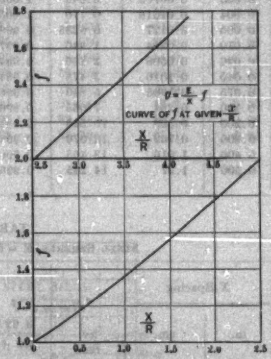


FIG. 10—FOR NON-GROUNDED SPHERES

The gradient for the non-grounded case may be conveniently calculated by use of the curve Fig. 10. The gradient on the line connecting sphere centers at any distance a from the sphere surface may be calculated from the complicated equation

$$g_a = \frac{E}{X}\left\{\frac{2\,x^2\,[x^2\,(f+1) + 4\,(X/2 - a)^2\,(f-1)]}{[x^2\,(f+1) - 4\,(X/2 - a)^2\,(f-1)]^2}\right\}^\dagger \quad (7)$$

*See G. R. Dean, *G. E. Review* March, 1913. Russel—*Philosophical Mag.* 1906.

†G. R. Dean—*G. E. Review*, March, 1913. *Physical Review*. Dec. 1912 and April 1913.

Some of the experimental values are given in Tables IV, V, VI, VII, VIII, IX. Typical voltage gradient curves are shown in Figs. 11, 12, 13 and 14.

TABLE IV

STEEL SPHERE $R = 0.158$ CM. DIAM. = 1/8 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273+t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.358	1.009	0.502	199.0	0.01598
0.002	0.00508	0.515	1.009	0.722	143.5	0.03196
0.003	0.00762	0.646	1.009	0.907	121.0	0.04794
0.004	0.01016	0.770	1.000	1.089	109.5	0.06392
0.005	0.0127	0.9235	0.9985	1.3085	105.7	0.0799
0.010	0.0254	1.440	0.997	2.045	85.0	0.1598
0.020	0.0508	2.150	0.984	3.090	67.5	0.3196
0.040	0.1016	3.475	0.984	5.000	60.2	0.6392
0.075	0.1905	5.840	0.9965	8.300	62.75	1.1985
0.100	0.254	7.065	0.9965	10.035	63.4	1.598
0.200	0.508	10.545	0.9840	15.170	68.85	3.195
0.300	0.762	12.070	0.992	17.200	68.8	4.793
0.400	1.016	13.465	0.9965	19.135	71.95	6.39
0.500	1.27	14.245	0.9965	20.14	73.075	8.00

TABLE V

STEEL SPHERES $R = 0.555$ CM. DIAM. = 7/16 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273+t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.384	0.995	0.545	215.3	0.00458
0.002	0.00508	0.546	0.995	0.775	153.0	0.00916
0.003	0.00762	0.692	0.995	0.982	129.4	0.01374
0.004	0.01016	0.787	0.9995	1.1125	110.25	0.01832
0.005	0.0127	0.847	0.9995	1.209	96.0	0.0229
0.010	0.0254	1.160	0.993	1.653	66.1	0.0458
0.020	0.0508	2.030	0.993	2.895	58.7	0.0916
0.040	0.1016	3.430	0.993	4.890	51.2	0.1832
0.075	0.1905	5.750	0.993	8.200	48.2	0.344
0.100	0.254	7.160	0.986	10.280	46.9	0.458
0.200	0.508	12.400	0.986	17.800	46.4	0.916
0.300	0.762	17.000	0.992	24.250	48	1.374
0.400	1.016	20.500	0.992	29.250	49	1.832
0.500	1.270	23.400	0.992	33.400	49.7	2.29

TABLE VI

BRASS SPHERES $R = 1.27$ CM. DIAM. = 1 IN.

X-Spacing		e_{eff}	δ	e_{max}	$\mathcal{E}_{max}$	
in.	cm.	kv. read	$\frac{3.92\,b}{273+t}$	$\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	$\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.387	1.01	0.542	213.4	0.002
0.002	0.00508	0.608	1.01	0.852	168.0	0.004
0.003	0.00762	0.712	1.01	0.998	131.0	0.006
0.004	0.01016	0.757	1.01	1.060	104.7	0.008
0.005	0.0127	0.808	1.01	1.132	89.5	0.01
0.010	0.0264	1.310	1.0095	1.836	72.72	0.02
0.020	0.0508	2.160	1.011	3.020	60.25	0.04
0.040	0.1016	3.520	1.005	4.950	50.0	0.08
0.075	0.1905	5.680	1.005	8.000	44.0	0.15
0.100	0.254	7.120	1.005	10.020	42.25	0.20
0.200	0.508	12.670	1.005	17.81	39.9	0.40
0.300	0.762	18.00	1.005	25.34	40.2	0.60
0.400	1.016	22.87	1.008	32.35	40.75	0.80
0.475	1.205	26.15	1.008	36.70	41.1	0.95

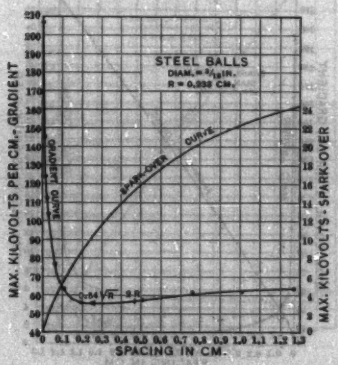


FIG. 11

TABLE VII

BRASS SPHERES $R = 3.33$ CM. DIAM. = 2⅝ IN.

X-Spacing		e_{eff}	δ	e_{max}	E_{max}	
in.	cm.	kv. read	$\frac{3.92\,b}{273+t}$	$\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	$\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00245	0.3625	1.0285	0.4975	196.05	0.000763
0.002	0.00508	0.531	1.0305	0.7295	143.65	0.001525
0.003	0.00762	0.654	1.027	0.8995	118.15	0.002285
0.004	0.01016	0.7755	1.0265	1.0685	105.2	0.00305
0.005	0.0127	0.8447	1.0165	1.1717	92.312	0.00382
0.010	0.0254	1.070	0.998	1.518	60.0	0.00764
0.020	0.0508	1.357	1.002	2.620	51.8	0.01528
0.040	0.1016	3.275	1.002	4.620	45.95	0.03056
0.075	0.1905	5.430	1.002	7.660	41.0	0.05730
0.100	0.254	6.920	1.002	9.770	39.5	0.0764
0.200	0.508	12.400	1.002	17.500	36.26	0.1528
0.300	0.762	17.700	1.002	25.000	35.4	0.2292
0.400	1.016	22.700	1.002	32.000	34.8	0.3056
0.500	1.27	27.750	1.002	39.2000	34.95	0.382

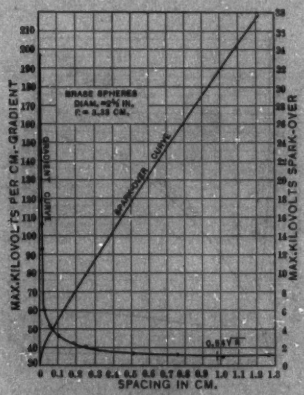


FIG. 12—PLOTTED FROM TABLE VII

TABLE VIII

BRASS SPHERES $R = 6.25$ CM. DIAM. = 4 15/16 IN.

X-Spacing		e_{eff}	δ	e_{max}	g_{max}	
in.	cm.	kv. read	$\frac{3.92\,b}{273+t}$	$\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	$\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.001	0.00254	0.378	0.993	0.538	212.0	0.000406
0.002	0.00508	0.475	0.992	0.678	133.3	0.000812
0.003	0.00762	0.590	0.992	0.841	110.4	0.00122
0.004	0.01016	0.710	0.996	1.008	99.3	0.00162
0.005	0.0127	0.833	1.006	1.1695	92.1	0.00203
0.010	0.0254	1.230	1.008	1.725	68.0	0.00406
0.020	0.0508	1.92	1.021	2.660	52.5	0.00812
0.040	0.1016	3.29	1.019	4.57	45.2	0.01624
0.075	0.1905	5.55	1.019	7.72	40.9	0.03042
0.100	0.254	7.02	1.022	9.72	38.8	0.0406
0.200	0.508	12.53	1.022	17.35	35.1	0.0812
0.300	0.762	17.73	1.022	24.55	33.62	0.1218
0.400	1.016	22.9	1.021	31.70	33.0	0.1624
0.500	1.27	27.85	1.021	38.58	32.5	0.2030

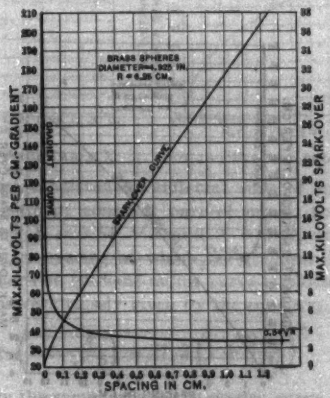


FIG. 13—PLOTTED FROM TABLE VIII

TABLE IX

BRASS SPHERES $R = 12.5$ CM. DIAM. = 9.84 IN.

X-Spacing in.	X-Spacing cm.	e_{eff} kv. read	δ $\frac{3.92\,b}{273+t}$	e_{max} $\frac{\sqrt{2}\,(e_{eff.})}{\delta}$ kv. corr.	g_{max} $\frac{e_{max}}{X}\,f$ kv. per cm.	$\frac{X}{R}$
0.005	0.0127	0.8076	1.0226	1.1156	87.9	0.00101
0.010	0.0254	1.22	1.021	1.689	66.53	0.00203
0.020	0.0508	2.0506	1.0313	2.8396	55.9	0.00406
0.040	0.1016	3.3876	1.0223	4.683	46.2	0.00813
0.100	0.254	7.026	1.020	9.750	38.61	0.02032
0.200	0.508	12.54	1.0116	17.445	34.82	0.04064
0.300	0.762	17.91	1.016	24.92	33.5	0.06096
0.400	1.016	22.825	1.0103	31.765	32.05	0.08128
0.500	1.27	27.63	1.0103	38.67	31.53	0.1016
1.000	2.54	53.0	1.000	74.9	31.6	0.2032
1.500	3.81	75.3	1.000	106.3	30.9	0.3048
2.000	5.08	96.4	1.000	136.2	30.5	0.4064
2.500	6.35	117.4	1.000	166.0	30.7	0.5080
3.000	7.62	139.2	1.000	196.9	31.2	0.6096
3.500	8.89	158	1.000	223.4	31.3	0.7112
4.000	10.16	174.9	1.000	247	31.0	0.8128
4.500	11.43	190.8	1.000	269.5	31.0	0.9144
5.000	12.70	203.6	1.000	287.2	30.8	1.016

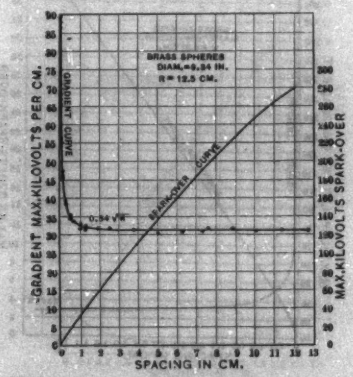


FIG. 14—PLOTTED FROM TABLE IX

TABLE X

Radius cm. R	Spacing cm. X Where g_2 begins to increase	g_2 max. kv. per cm. Constant part of curve	g_2 max. kv. per cm. Average between $0.6\sqrt{R}$ and $3R$
0.159	0.18	63.8	
0.238	0.25	55.6	
0.356	0.26	51.4	
0.555	0.40	46.9	
1.27	0.51	39.9	42.5
2.54	0.85	36.8	38.4
3.33	0.95	34.8	37.1
6.25	1.30	32.5	33.5
12.5	2.0	31.3	31.3

$$g_2 = 27.2\left(1 + \frac{0.54}{\sqrt{R}}\right)$$

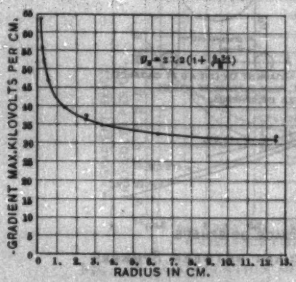


FIG. 15—PLOTTED FROM TABLE X

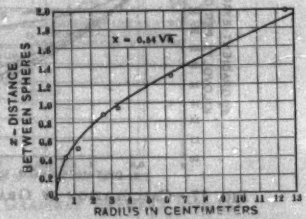


FIG. 16—PLOTTED FROM TABLE X

In Table X are tabulated for different sizes of spheres the spark-over gradients at constant part of curve, the average gradients between $X = 0.54\sqrt{R}$ and $X = 3R$, and the approximate minimum spacing at which the gradient begins to increase in value. The gradient-radius curve is plotted in Fig. 15. This curve is very closely given by the equation

$$g_0 = g_0\left(1 + \frac{k}{\sqrt{R}}\right) = 27.2\left(1 + \frac{0.54}{\sqrt{R}}\right)^{*} \qquad (8)$$

which has exactly the same form as the similar curve for cylinders. The values of g_0 is, however, lower than for the balanced field of a wire in a cylinder.

*This is given for theoretical reasons rather than for exact practical calculations.

For a wire in a cylinder $g_0 = 31$

For parallel wires $g_0 = 30$

For spheres $g_0 = 27 - 28$

It is probable that the true strength of air is 31 kv. per cm. as represented by the balanced field; it is apparently less for parallel wires due to unbalanced field, and the apparent value is still less for spheres where the field is unbalanced to a still greater extent.

The curve between the sphere radius and the *approximate* minimum spacing below which the gradient begins to increase is plotted in Fig. 16 from Table X. The curve is represented by the equation

$$X = 0.54\sqrt{R} \tag{9}$$

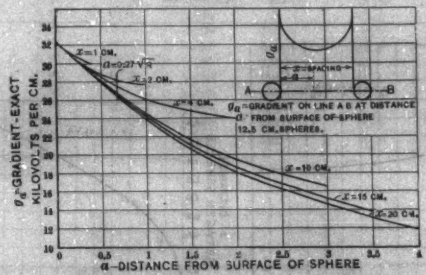


FIG. 17—CALCULATION OF GRADIENT BETWEEN SPHERES

which means that when the spacing is less than $0.54\sqrt{R}$ the gradient increases in value, at first slowly, then very rapidly.

It is now interesting to investigate the meaning of equation (8). In Figs. 17 and 18 the exact gradient is plotted from equation (7) for different distances from the sphere surface on the line connecting the centers, and at given spacings, as indicated by the small diagram in the upper corner of the figure.

It is seen that for small distances from the sphere surface the curves for the different spacings fall together. Over this small range the gradient g_a at any point a cm. from the sphere surface on the center line may be found

$$g_a \cong \frac{E}{R + 2a}\left(\frac{R}{X}\right)f \tag{10}$$

The only excuse for using this approximation, which holds only for very small values of a and is only true when $a = 0$, is that (7) is too complicated to handle. The error due to this approximation is shown in Table XI. Then

$$g_s = \frac{E_s}{X} f = \frac{E_s}{R} \left(\frac{R}{X} f \right) \text{ Exact mathematical} \tag{6}$$

$$g_s = g_0 \left(1 + \frac{k}{\sqrt{R}} \right) \text{ Experimental for approximately constant part of curve.} \tag{8}$$

$$g_a \cong \frac{E}{(R+2a)} \left(\frac{R}{X} f \right) \text{ Approximate mathematical} \tag{10}$$

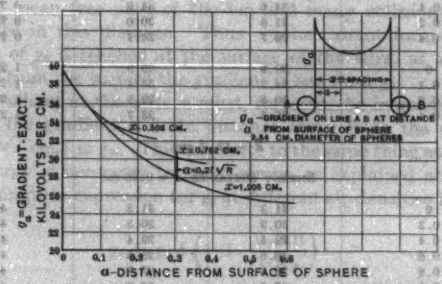


FIG. 18—CALCULATION OF GRADIENT BETWEEN SPHERES

Equating equations (6) and (8)

$$\frac{E_s}{R} \left(\frac{R}{X} f \right) = g_0 \left(1 + \frac{k}{\sqrt{R}} \right)$$

$$g_0 = \frac{E_s}{(R + k\sqrt{R})} \left(\frac{R}{X} f \right)$$

which is the same form as (10), or which means that at a distance

$$\frac{k\sqrt{R}}{2} = \frac{0.54\sqrt{R}}{2} = 0.27\sqrt{R} \text{ cm.}$$

from the sphere surface the gradient at rupture is always approximately constant, and is g_0. Breakdown must take place at approximately $a = 0.27\sqrt{R}$ cm. from the sphere surface; therefore at the spacing $2a = 0.54\sqrt{R}$ the gradient begins to increase. This is approximately so, as shown in Fig. 16 and equation (10). The increase is slow at $X = 2a$ but becomes very rapid at $X = a$. Looking at Fig. 17, it is seen that at $a = 0.27\sqrt{R}$ the gradient

TABLE XI

$R = 1.27$ cm.

a	g_a Exact	g_a Approx.	X
Energy Distance $a = 0.27\sqrt{R} = 0.3$ cm.			
0	39.9	39.9	0.76
0.1	34.6	34.0	0.76
0.2	31.9	30.0	0.76
0.4	29.7	24.1	0.76
0	39.9	39.9	1.21
0.1	34.2	33.4	1.21
0.2	30.5	29.5	1.21
0.4	26.5	23.7	1.21
$R = 12.5$ cm.			
Energy Distance $a = 0.95$ cm.			
0	31.3	31.3	4
0.2	30.3	30.3	4
0.4	29.5	29.4	4
0.6	28.6	28.5	4
0.8	28.3	27.7	4
1.0	27.5	26.9	4
0	31.3	31.3	10
0.2	30.3	30.3	10
0.4	29.5	29.4	10
0.6	28.6	28.7	10
0.8	28	27.7	10
1.0	27.5	26.9	10

is not exactly constant for different spacings; that is, the curves do not fall together. This means that g_s and k in equation (8) cannot be *exactly* constant for a given radius but must also be a function of X.* This is experimentally shown to be the case.

Application of the Electron Theory

The electron theory may also be very well applied in agreement with the above, as has been already pointed out. Briefly:

When low potential is applied between two conductors any

*See footnote page 1781.

free ions at the surface are set in motion. As the potential and, therefore, the field intensity or gradient is increased, the velocity of the ions increases. At a gradient of $g_0 = 31$ kv. per cm. ($\delta = 1$) the velocity of the ions becomes sufficiently great over the mean free path to form other ions by collision with molecules. This gradient is constant, and is called the dielectric strength of air. When ionic saturation is reached at any point the air becomes conducting, and glows, or there is corona or spark.

Applying this to a wire in the center of a cylinder. When a gradient g_v is reached at the wire surface any free ions are accelerated and produce other ions by collision with molecules, which are in turn accelerated. The ionic density is thus gradually increased by successive collision until at $0.301\sqrt{r}$ cm. from the wire surface, where $g_0 = 31$, ionic saturation is reached, or corona starts. The distance $0.301\sqrt{r}$ cm. is of course many times greater than the mean free path of the ion and many collisions must take place in this distance. Thus corona cannot form when a gradient of g_0 is reached at the surface of the wire, as at any distance from the surface the gradient is less than g_0.

The gradient at the surface must, therefore, be increased to g_v so that the gradient a finite distance away from the surface ($0.301\sqrt{r}$ cm.) is g_0. This amounts to the same thing as saying that energy is necessary to start corona, as explained above.

The complete expression for g_v at different air densities is

$$g_v = g_0\,\delta\left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \tag{11}$$

This means that g_0, the strength of air, varies directly with δ. g_v, however, cannot vary directly with δ because, with the greater mean free path of the ion at lower air densities, a greater "accelerating", or energy, distance is necessary. In the equation $a = 0.301\sqrt{r}/\delta$, that is, a increases with decreasing δ.

When the conductors are placed so close together that the free accelerating, or energy storage, distance is interfered with, the gradient g_v must be increased in order that ionic density may be reached in this limited distance. This is shown experimentally by sphere-gap tests.

A paper presented at the 30th Annual Convention of the American Institute of Electrical Engineers, Cooperstown, N.Y., June 27, 1913.

Copyright 1913. By A.I.E.E

AN OSCILLOGRAPH STUDY OF CORONA

BY EDWARD BENNETT

INTRODUCTION

In the investigations which have heretofore appeared, dealing with the formation of corona around high-tension wires, the effect of the corona, or the partial breakdown of the air, on the charging current of the wires has not been determined by direct experimental methods. Oscillograms of the charging current of a conductor surrounded by corona not only afford a check on conclusions arrived at by independent methods of observation, but also throw additional light on the nature of the failure of the air around the conductor.

Three methods of using the oscillograph to determine the wave form of the charging current of a wire present themselves.

1. The oscillograph may be connected between the wire and the high-tension transformer which charges the wire.

2. The wire may be surrounded by a metal cylinder insulated from earth, and the displacement from the wire may be collected by this cylinder and sent to earth through the oscillograph as shown in Fig. 1.

3. The wire may be surrounded by an insulated metal cylinder as in the second method, but in this case the wire is connected to earth through the oscillograph, while the metal cylinder is maintained at the high potential.

The first method involves either:

a. The use of a current transformer with insulation between primary and secondary sufficient to withstand the potential between wire and earth and with the primary supplied by the charging current of at least several thousand feet of wire; or

b. The connection of the vibrator of the oscillograph directly in the high-tension line, and therefore the insulating of the entire oscillograph from earth. Neither of these alternatives is very satisfactory.

The third method is very similar to, and has most of the advantages of the second method, which is discussed at length hereafter. The third method is, however, not quite as convenient to use in crowded quarters as is the second.

Second Method. In collecting the charging current of the wire by a metal cylinder, as in the second method, it is to be noted that an oscillograph of the type used requires a current of from 0.05 to 0.08 peak amperes per centimeter deflection of the spot of light. The charging current of a wire 0.5 cm. in diameter at the voltage at which corona is visible is only 0.054 r.m.s. amperes per 1000 ft. (300 m.) at a frequency of 60 cycles. Therefore if the charging current of the wire is passed directly through the vibrator of the oscillograph, it will require at least 400 ft. (120 m.) of wire and enclosing cylinder to furnish enough current for satisfactory deflections. If, however, as shown in Fig. 2, a current transformer with a primary to secondary current ratio of 1 to 100 be interposed between the collecting cylinder and the vibrator of the oscillograph, satisfactory oscillograms of the charging current may be obtained with a length of wire and cylinder of only 10 ft. (3 m.). With this arrangement the conditions surrounding the wire may be easily varied and controlled. For example, the wire may be readily cleaned or polished, or the cylinder may be closed at both ends and partially exhausted. The oscillograms herein contained were obtained by the use of a collecting cylinder[1] and current transformer as outlined above.

This paper contains:

a. A description of this method and the apparatus used for obtaining oscillograms showing the form of the charging current of a 10-ft. (3-m.) length of wire at potentials below and above the corona voltage.

b. A series of oscillograms taken with the apparatus under varying air pressures and varying voltages on different conductors. These oscillograms show the marked asymmetry in the current after corona forms, the relation between power loss and im-

1. Much of the apparatus used in this work has been prepared by G. B. Blake, C. R. Higson and B. E. Miller in preliminary work along this line. In the experimental work great assistance has been rendered by B. E. Miller and L. E. A. Kelso.

pressed voltage, the start of corona after switching, the voltage at which ionization sets in, the marked difference in the results at high and low air pressures, etc.

II—Method and Apparatus

To obtain oscillograms of the charging current of a short length of wire, the circuits and apparatus represented in Fig. 2

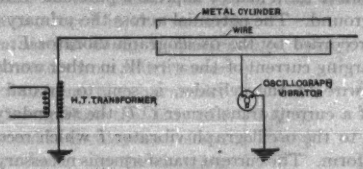


Fig. 1—Method of Obtaining Oscillograms of the Charging Current of a Wire

were used. In this figure, W is the wire whose charging current oscillogram is desired. This wire is stretched along the axis of the metal cylinder C and is held taut by the spring S. Two different cylinders were used at different times during the tests: an 8-in. iron pipe 20.6 cm. in diameter by 518 cm. long, and a cylinder of galvanized iron wire mesh. The galvanized mesh

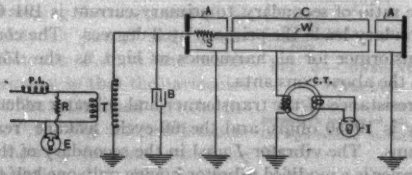


Fig. 2—Connections for Oscillograms of the Charging Current of a Wire

wire was 0.112 cm. in diameter, the mesh was 1.27 cm. square; the diameter of the mesh cylinder was 36.8 cm. and the length 311 cm. Grounded end shields A, 60 cm. long, were used at each end of the mesh cylinder. No shields were used with the iron pipe.

The wire W was connected to one terminal of the high-tension

winding of a 50-kv., 20-kw. transformer T, the other terminal of which was grounded. The voltage impressed on the primary was regulated by an induction regulator. B is a bank of Leyden jars so adjusted with respect to the air-core inductance $P.I.$ inserted in the primary that the circuit offers a much higher impedance to any harmonics in the generator voltage than to the fundamental. This serves to sift out all harmonics in the generator wave form and to impress a pure sine voltage between wire and ground. The potential across the primary of the transformer is recorded by the oscillograph vibrator E.

The charging current of the wire W, in other words the current from the wire to the cylinder, is sent to ground through the primary of a current transformer $C.T.$ the secondary of which is connected to the oscillograph vibrator I which records the current wave form. The current transformer is necessary because the current from wire to cylinder is of the order of half a milliampere while the vibrator I requires 50 milliamperes for a satisfactory deflection.

Frequency. All oscillograms and measurements were obtained at a frequency of 60 cycles per second.

Current Transformer. The current transformer is arranged for ratios of transformation of approximately 100, 200 and 600. At 60 cycles with the 100 to 1 connection, the ratio of the secondary to primary current is 98.9 to 1 and the secondary current leads the primary current by 1.3 degrees. With the 200 to 1 connection the ratio of secondary to primary current is 194.6 to 1 and the secondary leads the primary by 3 degrees. The constants of the transformer for all harmonics as high as the 15th are as good as the above constants.

The resistance of the transformer and vibrator reduced to the primary is 19850 ohms, and the 60-cycle leakage reactance is 4800 ohms. The vibrator I used in the secondary of the current transformer is a modified vibrator having only one half the length of silver of the standard vibrator and a resistance of 0.6 ohms.

To show the faithfulness with which harmonics are reproduced in the secondary of the current transformer, oscillogram 194 (Fig. 14) is here reproduced. This oscillogram was obtained by using the Fig. 2 connection with the following modifications. The inductance $P.I.$ was omitted and the charging current of the condenser B was passed directly through the third vibrator P of the oscillograph by connecting the vibrator in the circuit between B and ground.

The curve P was traced by the vibrator P and the curve S by the vibrator in the secondary of the current transformer. Below the corona voltage, the charging current of the condenser B and of the wire in the cylinder C should have the same wave forms; any appreciable errors introduced by the current transformer should cause an appreciable difference in the shapes of the current wave forms P and S. An inspection of the oscillogram shows that harmonics in the primary of the current transformer are accurately reproduced in the secondary.

Sifting Out the Harmonics in the Generator Voltage. The voltage of the generator from which power was obtained contains high harmonics of such small amplitude that they can just be detected in oscillograms of the voltage wave form. In the charging current of the wire, however, these harmonics are amplified to such an extent that they entirely mask the effect of the first stages of corona formation. The record of the oscillograms is far more intelligible if the harmonics are all sifted out, so that the effect of the corona is superimposed on a pure sine curve. This was accomplished as previously stated by proportioning the reactances of the bank of Leyden jars B and the air-core inductance $P.I.$ in the transformer primary so that the harmonics would all be consumed in the inductance, $P.I.$ Fig. 3 is a schematic diagram showing the constants of the circuit consisting of the high-tension transformer with the condensers and inductance for sifting out the harmonics. All resistances and reactances are reduced to the high tension circuit and are expressed in megohms. Oscillograms 177 to 181 are intended to contrast the results obtained with and without sifting out the harmonics. These oscillograms were all obtained with the Fig. 2 connections using a polished copper wire 0.227 centimeters in diameter and an iron pipe 20.6 centimeters in diameter. Corona was visible around the wire at 18 kv. Oscillograms 180 and 181 were taken without the condenser B and the inductance $P.I.$,

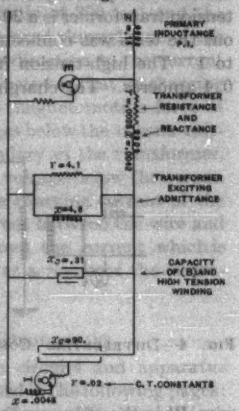


FIG. 3—CONSTANTS OF THE CIRCUITS

Resistances and reactances are expressed in megohms, all reduced to the high-tension circuit: frequency 60 cycles.

below and above the corona voltage respectively. It is impossible to detect the harmonics in the e.m.f. wave form, but they render the current wave form so jagged that the details brought out in oscillogram 178 would be lost. Oscillograms 177 to 179 were obtained with the harmonics sifted out.

High-Tension Transformer-Phase Relations of Primary and Secondary Voltages. Since the voltage recorded on all oscillograms is the voltage impressed on the primary of the step-up transformer it is necessary to determine the phase relation between the primary and the high-tension voltage. The high-tension transformer is a 20-kw. 50-kv. transformer which throughout the tests was connected for a ratio of transformation of 250 to 1. The high-tension full load current of this transformer is 0.4 amperes. The charging current of the condenser B and the

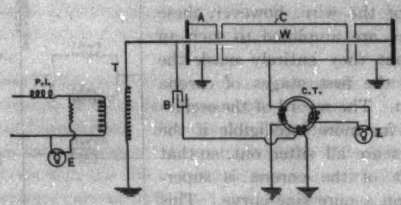


FIG. 4—DIFFERENTIAL CONNECTIONS FOR ELIMINATING CHARGING CURRENT

wire W is the only current delivered by the transformer. The charging current of the wire is about 1/200 of the charging current of the condenser or is negligible in comparison. The capacity of the condenser B was varied within narrow limits during the tests but was generally kept at 7.3×10^{-9} farads. At 60 cycles and 50 kv. the charging current of this capacity is 0.14 amperes or only 35 per cent of the full load current of the transformer. Since at full load the resistance and the reactance drops of the transformer are 2.3 per cent and 3.5 per cent respectively, it follows that the high-tension voltage leads the primary or recorded voltage by 0.5 degrees and is 1.2 per cent higher than the no-load voltage.

Since the current in the secondary of the current transformer, —and through the current vibrator—leads the current in the primary of the transformer—the true charging current,— by

1.3 deg., it follows that the phase relation of current to voltage as recorded on the oscillograms is correct to within one degree. To get the correct relations the voltage wave should be advanced by 0.8 degree.

Differential Connection for Eliminating the Charging Current. At voltages slightly higher than the voltage at which corona forms around a wire, the effect of ionization on the current wave form can be shown to better advantage by neutralizing the charging current of the wire in the manner shown in Fig. 4.

The connections of Fig. 4 differ from those of Fig. 2 in that the current transformer is connected for a ratio of 200 to 1 and the charging current of the condenser *B* is passed through one of the coils of the transformer, in the opposite direction to the current in the primary. The capacity of *B* is adjusted so that its charging current just balances and neutralizes the magnetomotive force of the charging current of the wire at voltages below the corona voltage. The current vibrator in the secondary of the transformer, as a result, traces a straight line at any voltage below the corona voltage. Above the corona voltage the charging current of the condenser *B* no longer balances the current between the wire and cylinder, and the current vibrator shows the current which is superimposed on the charging current as a result of the ionization around the wire.

III—Observations and Deductions

The oscillograms obtained with the circuits and apparatus above described are grouped and discussed in the following pages:

Oscillogram Notation. Explanation of Terms. The connections of the oscillograph were such that for all films the following relations apply:

A positive deflection (a deflection above the zero line) of the current vibrator indicates a current from the enclosing cylinder to the wire *W*, *i.e.*, the wire is cathode or negative to the cylinder.

A negative deflection of the current vibrator therefore indicates a current from wire to enclosing cylinder, *i.e.*, the wire is anode. The same conventions of course must hold for deflections of the potential vibrator. On some of the films these conventions have been indicated by the use of two concentric circles representing the wire and its enclosing cylinder, and appropriately marked + and −. Thus if the circles are placed above the zero line they indicate the polarities for positive deflections and the inner circle is marked − and the outer +. If the circles

are below the zero line they indicate the polarities for negative deflections and the inner circle is positive and the outer negative. On all oscillograms the current wave form is designated by i, the voltage wave by e.

Instant of Copious Ionization. Voltage at Copious Ionization. All oscillograms taken at a voltage high enough to cause the formation of corona are characterized by a sudden increase in the current similar to the increase which is shown at the instants t_1 and t_2 in Fig. 5. In the discussion of the oscillograms this instant of time, at which the current suddenly "shoots up," is designated as the "Instant of *Copious* Ionization." In specifying the instant of copious ionization, it is convenient to locate it with reference to the succeeding voltage peak; thus, the instant of copious ionization occurs n degrees ahead of the voltage peak.

The instantaneous value of the voltage between wire and cylinder at the instant of copious ionization is designated as the Voltage at Copious Ionization. "Instant of Ionization" conveys the impression that no ionization occurs during the part of the cycle immediately preceding the "Instant of Ionization." This notion may be very misleading; it is avoided by prefixing copious to ionization.

Hypothetical Gradient. If the air between the wire and the concentric cylinder used in these experiments acts as a pure dielectric, permitting of an elastic displacement only, the electric intensity or potential gradient g at any instant at a point at a distance x from the axis of the cylinders is

$$g = \frac{e}{\log \frac{b}{a}} \frac{1}{x} \tag{1}$$

in which e is the difference of potential between the cylinders at the instant.

b is the radius of the outer cylinder.

a is the radius of the wire.

This expression for the gradient does not apply if there is an accumulation of charge, that is, an excess of positive or negative ions in any region. The hypothesis under which the gradient is computed in equation (1), namely, that the gas permits of elastic displacement only, is untenable at potentials which cause corona around the inner cylinder. It may also be untenable at lower potentials. To avoid the mental confusion which may arise from

the use of an untenable hypothesis, a gradient computed by the use of equation (1) is called an "Hypothetical Gradient." The computed hypothetical gradient is a very useful notion only as long as its hypothetical nature is not lost sight of.

By the hypothetical surface gradient (*h.s.g.*) is meant the hypothetical gradient at the surface of the inner cylinder

$$h.\ s.\ g. = \frac{e}{a \log \frac{b}{a}} \tag{2}$$

General Experimental Observations. Oscillograms 183 to 186 and 187 to 191 are intended to illustrate the observations described below. These oscillograms were obtained with a polished steel wire 0.059 cm. in diameter in the 8-in. (20.6 cm.) iron pipe, at an air pressure of 74 cm. of mercury. The first four oscillograms were obtained with the Fig. 2 connections and the last four with the charging current of the wire neutralized by the differential connection of Fig. 4. Corona forms around this wire at 10.45 r.m.s. kv. between wire and cylinder. The hypothetical gradient in kv. per cm. at the surface of this wire equals 5.80 times the voltage between wire and cylinder.

If, as the voltage impressed between the polished wire W and cylinder of Fig. 2 is slowly increased, the charging current of the wire is observed on the tracing table of the oscillograph, the following relations are noted:

1. As the voltage is slowly increased, simultaneously,— that is, at the same voltage within several tenths of one per cent,— with the appearance of the bluish haze around the wire and the occurrence of the hissing sound, a small hump or peak appears on the current wave under each voltage peak. The voltage at which this occurs has been variously designated as the "visual critical voltage" or "corona voltage" for the particular wire and cylinder. The ordinates of the hump which is superimposed on the sine charging current show the instantaneous values of the increase in current resulting from ionization after the corona voltage is exceeded. Oscillograms 183, 184 and 188 show the appearance of the oscillograms at voltages slightly higher than the corona voltage.

2. When observing the current wave form on the tracing table of the oscillograph, the hump on the current wave form can generally be detected under the negative voltage peak at a volt-

age a few tenths of a per cent below the voltage at which the positive hump is detected. That is, the hump is first detected during the half cycle in which the wire is anode and the cylinder cathode. This condition, however, has never been recorded on any of the photographic records. It is possible that the negative hump is *detected* before the positive, not because ionization occurs at a lower voltage when the wire is anode than when it is cathode, but because the negative hump at its first appearance is short and peaked and is consequently easier to detect than the positive which is broad and low. This difference between the positive and negative humps at voltages slightly higher than the corona voltage is shown on oscillogram 183.

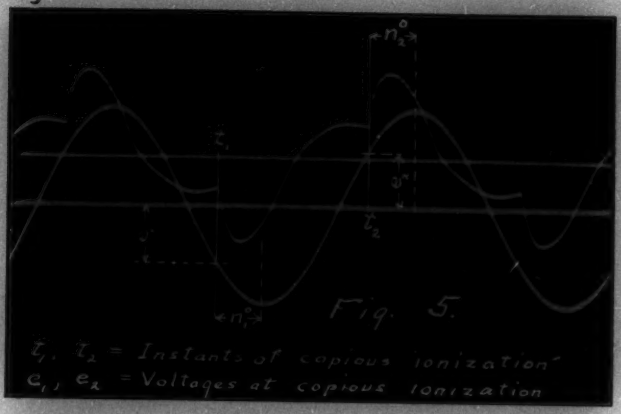
At pressures below 20 cm. of mercury, the positive hump is always observed before the negative appears; that is, copious ionization sets in at a lower voltage when the wire is negative than when it is positive.

3. On slowly lowering the voltage, the hump does not disappear from the current wave, nor does the hissing cease, until the voltage is from one to three per cent lower than the value at which they are first observed with increasing voltage. This would indicate that the ions persisting from any preceding half cycle facilitate the start of copious ionization in the succeeding half cycle.

4. At impressed voltages below the corona voltage the charging current of the wire is a sine current 90 deg. in advance of the voltage. That is, any loss resulting from ions present or ions formed below the corona voltage, is so small that it cannot be detected by the oscillograph.

5. The asymmetry in the current wave form to be noted in the series of oscillograms from 183 to 191 is not peculiar to the particular wire used, but is characteristic of all wires tried. The oscillation in the current occurs when the wire is cathode to the cylinder; only slight traces of an oscillation can be detected in the current when the wire is anode. The oscillation is more marked for finely polished wires than for weathered wires. This oscillation is later shown to be a result of the rapidity and suddenness with which the air in the vicinity of the wire loses its insulating properties.

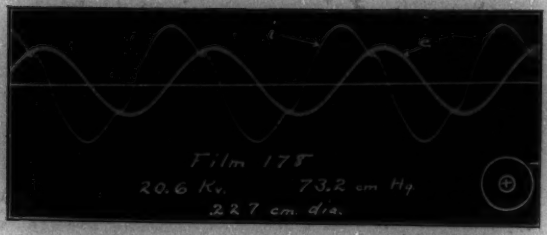
6. It will be noted that the increase in current resulting from ionization is not a smooth or gradual increase with the increasing voltage during the cycle; at a certain voltage the current "shoots" up very rapidly. The instant at which this occurs is designated

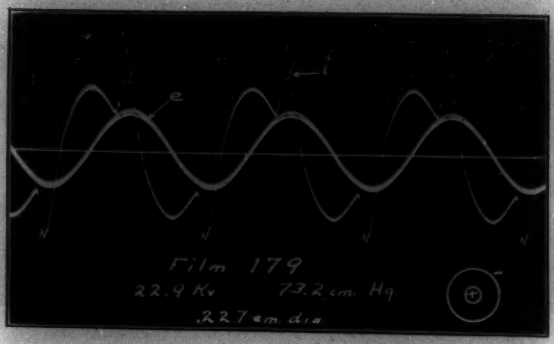

n_2^0
t_1
t_2
n_1^0
Fig. 5.
t_1, t_2 = Instants of copious ionization
e_1, e_2 = Voltages at copious ionization

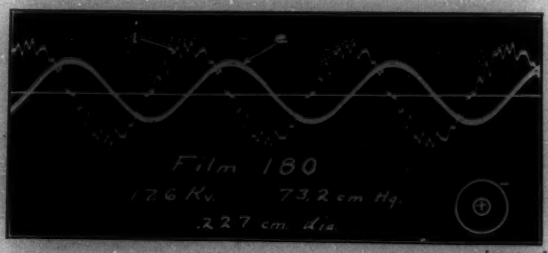
E_1
S_1
P
Fig. 14.
Film 194.

i
e
Film 177.
17.5 Kv. 73.2 cm Hg
2.27 cm. dia.

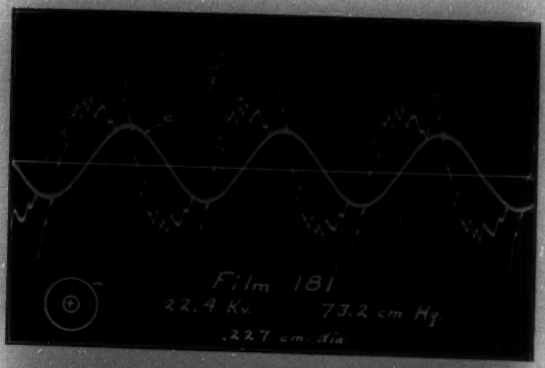
[BENNETT]

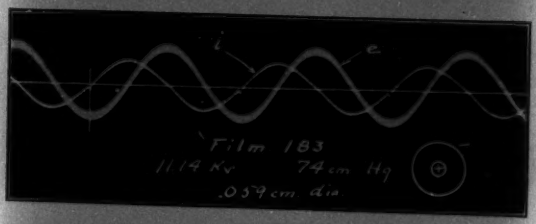

i
e
Film 178
20.6 Kv.
73.2 cm Hg
.227 cm. dia.
+
−

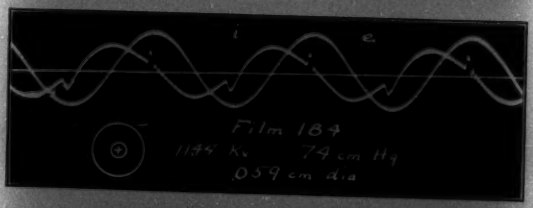

i
e
Film 179
22.4 Kv
73.2 cm. Hg
.227 cm. dia.
+
−

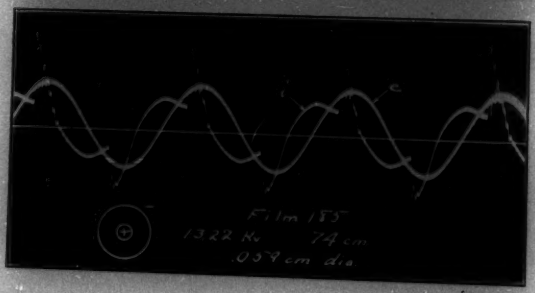

i
e
Film 180
17.6 Kv.
73.2 cm Hg.
.227 cm. dia.
+
−

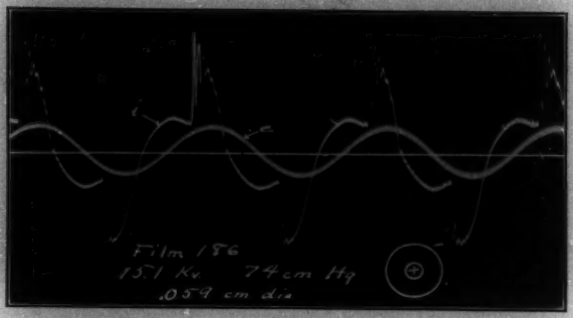
[BENNETT]


e
Film 181
22.4 Kv.
73.2 cm Hg
.227 cm. dia.


i
e
Film 183
1114 Kv.
74 cm Hg
.059 cm. dia.


i
e
Film 184
1144 Kv.
74 cm Hg
.059 cm. dia.


i
e
Film 185
1322 Kv.
74 cm
.059 cm. dia.


Film 186
13.1 Kv 74 cm Hg
.059 cm dia

Film 188
11.3 Kv 74.1 cm Hg
.059 cm. dia.

Film 189
11.55 Kv 74.1 cm
.059 cm dia

[BENNETT]

as the "instant of copious ionization." An inspection of the oscillograms obtained with the differential connection indicates that some current flows during each half cycle before copious ionization sets in.

The Oscillation in the Current. The interpretation of the oscillation to be observed in the current wave forms was for some time quite puzzling. The oscillation unquestionably indicates that there is a difference in the nature of the failure of the air, depending upon the direction of movement of the ions. The marked oscillation is always obtained when the wire is cathode, that is, when the negative ions move from a field of high to a field of low intensity and the positive ions in the reverse direction.

Both inductance and capacity are required for the oscillations shown on the oscillograms. Since the element of inductance in the part of the circuit between the wire and the cylinder is negligible, it did not seem possible that the oscillation could be in the movements of the ions in the ionized regions surrounding the wire. It was finally suspected that the oscillation resulted from the suddenness of the breakdown around the wire; and that the oscillatory circuit consisted of the current transformer and the capacity of the cylinder C to earth. The inductance of the circuit would be due to the leakage flux of the current transformer, which, in the paper previously referred to, is shown to be 12.7 henrys. The capacity to earth of the 10-ft. (3-m.) wire mesh cylinder and its connections was estimated at 2.3×10^{-10} farads. The natural frequency of oscillation of such a circuit is 2940 cycles per second; the critical resistance required to render the circuit non-oscillatory is 470,000 ohms. The frequency of oscillation found by scaling the films is 2720 cycles per second, which is 8 per cent lower than the computed frequency,—a fairly satisfactory agreement in view of the difficulty of estimating the capacity.

To determine beyond question the part of the circuit which takes part in the oscillation, the resistance, inductance, and capacity of the suspected oscillatory circuit were varied and the corresponding frequencies of oscillation were recorded on a series of oscillograms. These oscillograms were all obtained with a polished phosphor bronze wire 0.102 cm. in diameter in the wire mesh cylinder of 36.8 cm. diameter. The corona voltage for this wire is 14.7 r.m.s. kv. with increasing voltage. The oscillograms were all taken at approximately 15.2 r.m.s. kv.

Oscillogram 262 records the frequency of oscillation with the

Fig. 2 connections. As stated above, the recorded frequency is 2720 cycles per second, or 8 per cent lower than the frequency calculated from the roughly estimated constants. Contrast the amplitude of oscillation on oscillogram 262 with that on 259. Oscillograms 262 was obtained with the polished wire and 259 with the same wire before polishing. The amplitude of oscillation is much greater with the polished wire.

Fig. 6 shows the manner of connecting in additional inductance and capacity for the purpose of varying the constants of the oscillatory circuit. The additional resistance or the inductance was connected in series with the current transformer, between transformer and cylinder at D. The additional capacity, a 2.04×10^{-9} farad Leyden jar, F, was connected in parallel with the capacity of the wire mesh cylinder to earth.

Oscillogram 256 was obtained with an inductance of 24.6

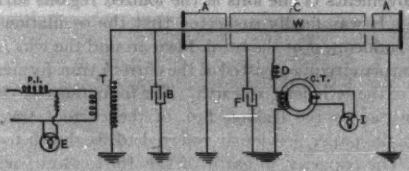


FIG. 6

henrys connected in at D and with the condenser F disconnected. The computed frequency is 1685 cycles per second and the frequency recorded on the film is 1640 cycles,—a difference of 3 per cent. Note that for this slowed down circuit, the breakdown of the air when the wire is anode is rapid enough to set up a slight oscillation.

Oscillogram 258 was now taken with the 24.6-henry inductance at D and the 2.04×10^{-9} farad condenser at F. The computed frequency is 545 cycles and the frequency recorded on the films 540 cycles per second,—a difference of one per cent.

Finally oscillogram 264 was taken without the condenser F or the inductance, but with a 0.94-megohm water tube resistance at D. Although this is twice the critical resistance of the oscillatory circuit of Fig. 2, there are still ripples to be detected in the positive hump; with this resistance the negative hump is perfectly smooth.

These tests confirm the conclusion that the oscillation results from the suddenness of the breakdown of the air around the wire and that the oscillatory circuit consists of the current transformer and the capacity of the cylinder C to earth. The inductance of the current transformer, by causing the overshooting, has served to bring out in a very striking manner the explosive suddenness with which the air around the wire loses its insulating properties when the wire is the cathode.

Relation between Watt Expenditure and the Impressed Voltage. The series of oscillograms from 261 to 269 was taken to determine the relation between the watt expenditure in the corona and the voltage impressed between wire and cylinder. These films were all obtained with the 0.102-cm. polished phosphor bronze wire in the mesh cylinder of 36.8 cm. diameter. Fig. 2 connections were used, modified, however, by inserting the 0.94-megohm resistance at D between the cylinder C and the current transformer in order to damp out the oscillation. The constant of the current vibrator was the same throughout this series. A critical examination of these films discloses the following relations:

1. With increasing voltages impressed between wire and cylinder, copious ionization occurs earlier and earlier in each half cycle. The relation between the impressed voltage and the angular interval between the instant of copious ionization and the succeeding voltage peak is shown in Fig. 7.

2. With increasing impressed voltages, the instantaneous voltage at which copious ionization sets in becomes smaller and smaller. The relation between the impressed voltage and the instantaneous voltage at the instant of copious ionization is shown in Fig. 7. At the higher voltages the period of ionization extends over a greater portion of each half cycle than at the lower voltages and the production of ions ceases later in each half cycle. The lowering, with increasing impressed voltage, of the voltage at which copious ionization sets in, may result from the great number of ions remaining from the previous half cycle at the higher voltages. Note that the voltage at which copious ionization occurs is lower when the wire is cathode than when it is anode.

3. A close examination of these oscillograms, especially at the lower voltages, indicates a slight current flow, such as might be attributed to the movement of ions, previous to the instant of copious ionization. This is brought out more clearly in oscillograms, 271 and 272, taken on the same wire, but with the charg-

ing current of the wire neutralized by the differential connections of Fig. 4. The current is quite appreciable before the start of copious ionization.

4. On these same oscillograms, 271 and 272, it will be noted that the current reverses before the voltage. This may indicate a reverse movement of the separated positive and negative ions before the reversal of the hypothetical gradient calculated from the instantaneous impressed voltages.

5. A casual inspection of the oscillograms 271 and 272 shows

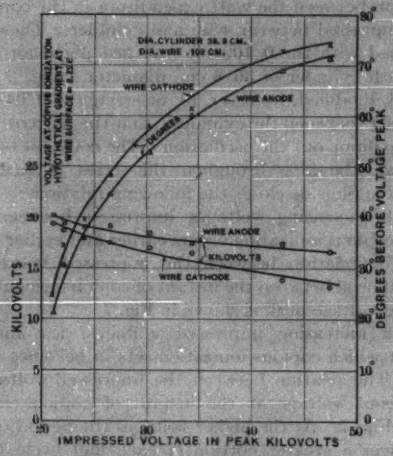
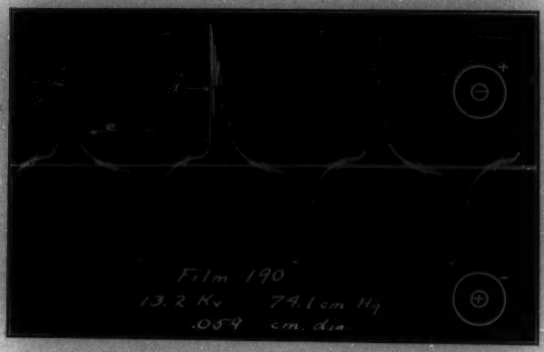


FIG. 7—RELATION BETWEEN IMPRESSED VOLTAGE AND (A) VOLTAGE AT COPIOUS IONIZATION (B) INSTANT OF COPIOUS IONIZATION

that at voltages slightly greater than the corona voltage the watt expenditure in the corona is greater during the negative half cycle—when the wire is anode—than during the positive half cycle. This is borne out by the calculations described in the next paragraph.

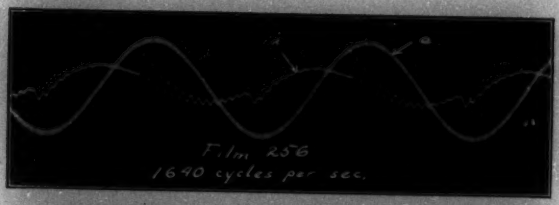
6. The watt expenditure between wire and cylinder was computed for the series of oscillograms 261 to 269 by placing each film over millimeter cross-section paper, reading off the corresponding values of voltage and current ordinates one millimeter apart,


i
e
+
−
Film 190
13.2 Kv 74.1 cm Hg
.059 cm. dia.

e
Film 262
2720 cycles per sec

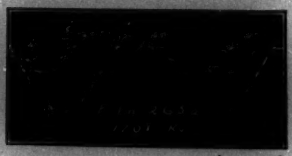
i
e
Film 259
2720 cycles per sec
Wire unpolished

(BENNETT)


Film 256
1640 cycles per sec.

Film 258
540 cycles per sec.

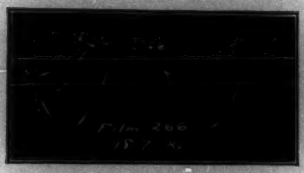
Film 264
With .94 megohms.
13.7 K.



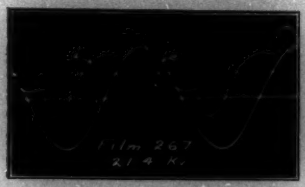
[BENNETT]

Film 265b
30.4 Kc.

Film 269
33.4 Kc.

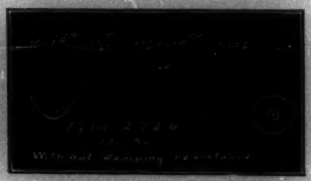

Film 266
18.7 Kc.

Film 271
12.7 Kc.


Film 267
21.4 Kc.

Film 272a
13 Kc.

Film 268
24.23 Kc.


Without damping resistance

[BENNETT]

computing therefrom the power curve, and taking the sum of the products for the positive half cycle, the negative half cycle and for the entire cycle. The results are tabulated below in Table I and are plotted in Fig. 8.

TABLE I

Impressed Voltage and Corresponding Watt Loss between Concentric Cylinders.

Inner cylinder—polished phosphor bronze wire 0.102 cm. in diameter.
Outer cylinder—of wire mesh. 36.8 cm. in diameter by 311 cm. in length.

Oscillogram	Peak kilovolts	Power expenditure in watts		
		Positive half cycle	Negative half cycle	Entire cycle
261	20.25	−0.006	−0.015	−0.011
263	21.05	0.818	1.05	+0.934
264	22.2	1.815	1.915	1.86
265 a	24.15	2.76	2.89	2.825
266	26.45	4.46	4.79	4.625
267	30.25	8.60	8.76	8.68
268	34.35	13.81	14.33	14.07
265 b	43.0	30.85	30.65	30.75
269	47.50	42.4	42.30	42.35

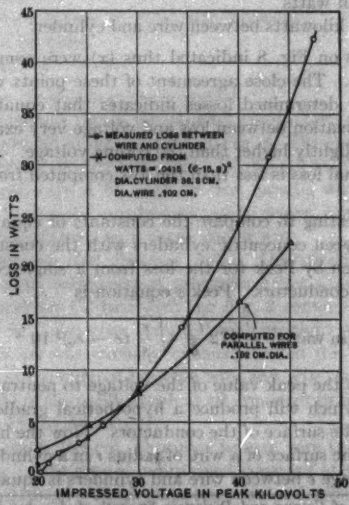


FIG. 8—RELATION BETWEEN IMPRESSED VOLTAGE AND POWER LOSS IN THE CORONA

At voltages slightly higher than the corona voltage, the loss is at least 20 per cent greater during the half cycle when the wire is anode than during the half cycle in which it is cathode.

This percentage difference becomes less with increasing voltage and is inappreciable at the higher voltages.

Peek[2] has shown that the loss P between the parallel wires is related to the voltage e between wire and neutral by an equation of the form

$$P = K (e - e_0)^2 \tag{3}$$

If the assumption is made that the equation of the loss-voltage curve plotted in Fig. 8 is of this form, and if the losses at 25 and 40 peak kv. are used to compute the values of the constants K and e_0, the following values are obtained:

$$K = 0.0415 \qquad e_0 = 15.8 \text{ peak kv.}$$

The resulting equation is

$$P = 0.0415 (e - 15.8)^2 \tag{4}$$

where

P = loss in watts

e = peak kilowatts between wire and cylinder.

The points on Fig. 8 indicated thus (x) were computed from equation (4). The close agreement of these points with the experimentally determined losses indicates that equation (4) expresses the relation between loss and voltage very exactly except at voltages slightly higher than the corona voltage. At low voltages the actual loss is less than the loss computed from equation (4).

It is interesting to compare the constants of equation (4) for the loss between concentric cylinders with the constants of the equation given by Peek for the loss from a single conductor of two parallel conductors. Peek's equation is

$$P \text{ (in watts)} = 172 \frac{l f}{\delta} \sqrt{\frac{r}{s}} (e - e_0)^2 \, 10^{-5} \tag{5}$$

in which e_0 is the peak value of the voltage to neutral, expressed in kilovolts which will produce a hypothetical gradient of 29.8 kilovolts at the surface of the conductors. Now the hypothetical gradient at the surface of a wire of radius r in a cylinder of radius b with a voltage e between wire and cylinders is equal to the hy-

2. *The Law of Corona and Dielectric Strength of Air*, by F. W. Peek, Jr., A. I. E. E. TRANSACTIONS, Vol. XXX, 1911, and Vol. XXXI, 1912.

pothetical gradient at the surface of the same wire if used as one of the parallel wires, provided the voltage from wires to neutral is equal to the voltage e and the distance s between the centers of the wires is equal to the radius b of the outer cylinder. As the basis on which to compare the loss from one wire of a pair of parallel wires with the loss between the same wire and a concentric cylinder let these conditions be imposed: (1) the voltage from the wire to neutral in the first case is to equal the voltage between wire and cylinder in the second case, (2) the distance between the centers of the parallel conductors is to equal the radius of the outer cylinder, thus making the hypothetical surface gradients equal in the two cases. Substituting in equation (5)

$l = 3.11$ meters.
$f = 60$ cycles
$\delta = 0.984$ for a temperature of 21 deg. cent. at a pressure of 73.8 cm.
$r = 0.051$ cm.
$s = 18.4$ cm.
$e_0 = 29.8\, r\, \delta \log s/r = 8.85$ peak kilovolts

it becomes

$$P = 0.0172\,(e - 8.85)^2 \qquad (6)$$

in which $e =$ peak kilovolts to neutral.

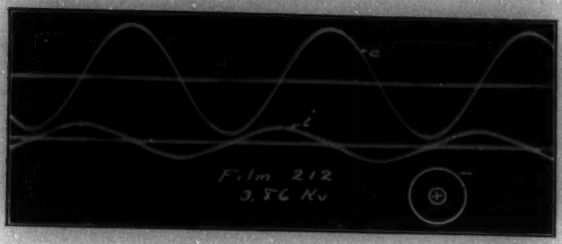
The loss-voltage curve for parallel conductors as computed from equation (6) is also plotted in Fig. 8. The great difference in the values of e_0 for the two cases,—15.8 peak kv. for concentric cylinders, and only 8.85 peak kv. for parallel wires,—was unexpected. No general conclusions can be drawn, however, on the basis of measurements on a single size of wire.

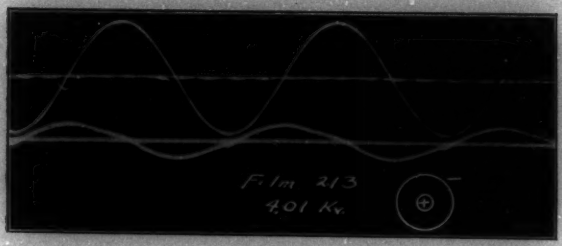
Observations at Air Pressure below Atmospheric. For the study of corona formation at pressures below atmospheric, the enclosing cylinder C, used with the Fig. 2 connections, was the 8-in. (20.6 cm.) iron pipe, provided with air-tight wooden bulkheads. The air was partially exhausted from this pipe and the wave form of the current between wire and pipe observed on the tracing table of the oscillograph at all pressures from atmospheric down to 0.13 cm. of mercury.

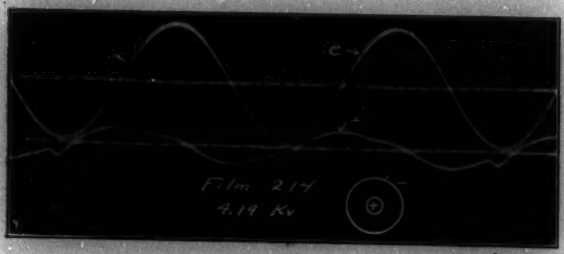
If, with the 0.102-cm. phosphor bronze wire in the pipe, the air pressure in the pipe is maintained constant at a given value, and the impressed voltage between wire and pipe is slowly increased, the following changes in the current wave form are noted with the increasing voltage:

1. At pressures between 76 cm. and 19 cm. of mercury:
   (a) The negative hump is detected first.
   (b) At a voltage about 0.2 per cent higher the positive hump is detected.
   (c) At a voltage still higher by 2 to 4 per cent, both humps "shoot up" in height very rapidly with slight increases in voltage.
   (d) At low voltages the negative hump is higher and of greater area than the positive but with increasing voltage the height of the positive hump overtakes and may slightly exceed the height of the negative.
   (e) The positive hump is markedly oscillatory—the negative is smooth.
   (f) The oscillograms do not differ materially in character from those at atmospheric pressures.
2. At pressures between 15 cm. and 3 cm. of mercury:
   (a) The positive hump is detected first.
   (b) Slight traces of oscillation are still to be detected in the positive hump.
   (c) The humps gradually get larger with increasing voltages, but do not at any time give the impression of "shooting up" rapidly with slight increases in the impressed voltage.
   (d) At low voltages the height of the negative hump exceeds the positive, but at higher voltages the height of the positive greatly exceeds that of the negative.
   (e) The series of oscillograms from 212 to 219 show the characteristic changes with increasing voltages for this range of pressures. These oscillograms were taken at a pressure of 13.7 cm. of mercury, with the Fig. 2 connections, and without using the 0.94-megohm resistance.
3. At pressures between 2.5 cm. and 0.13 cm. of mercury:

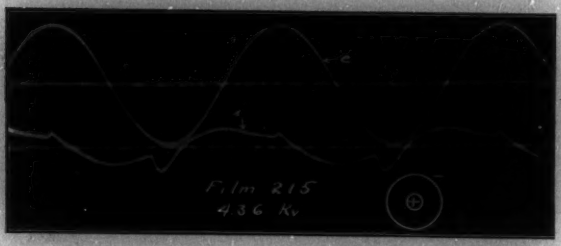
For this range of pressures the changes in the current wave form with increasing impressed voltage can best be described by reference to oscillograms 221 to 223 and 232, which show the characteristic appearance of the current wave form for this range of pressures. These oscillograms were all obtained with the Fig. 2 connections, modified, however, by connecting the potential vibrator E and its series resistance directly across the high-tension side of the step-up transformers. The voltage at

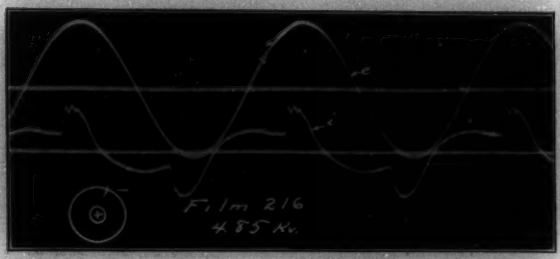


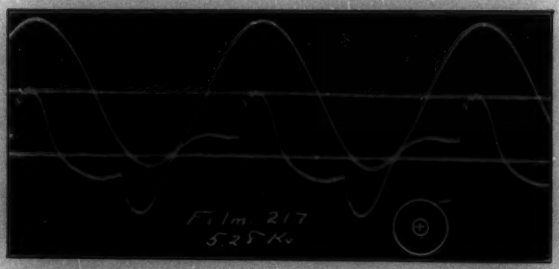




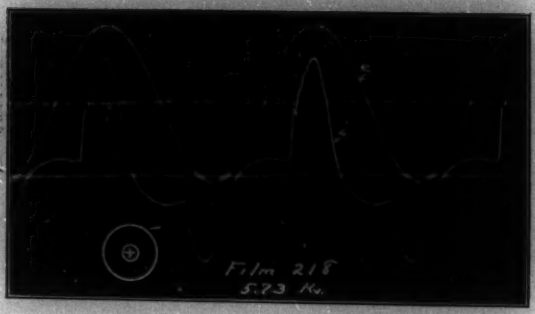
[BENNETT]



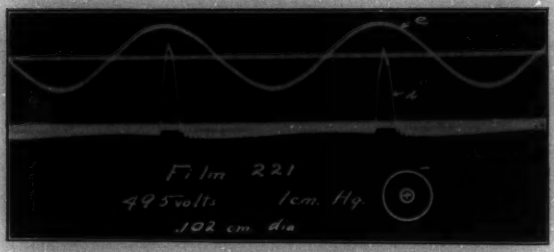


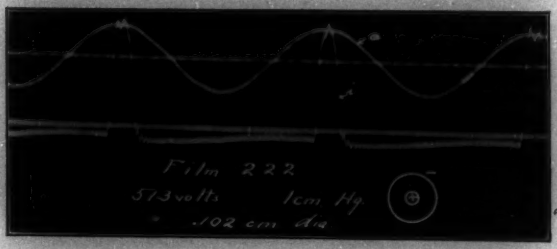


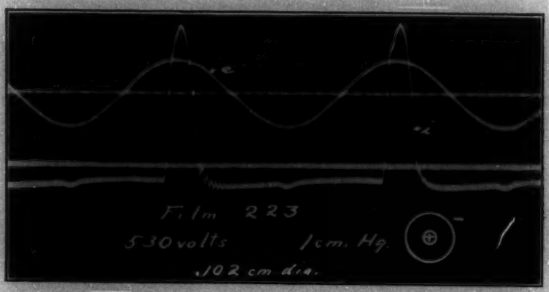
[BENNETT]



[BENNETT


e
i
Film 221
495 volts
1 cm. Hg.
.102 cm. dia


e
i
Film 222
513 volts
1 cm. Hg.
.102 cm. dia

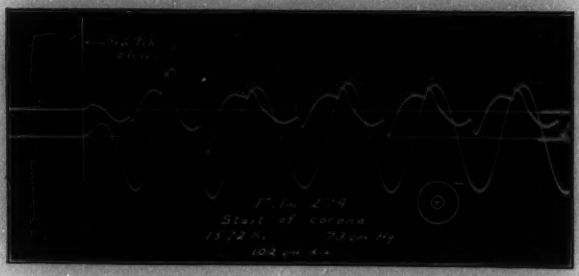

e
i
Film 223
530 volts
1 cm. Hg.
.102 cm. dia.

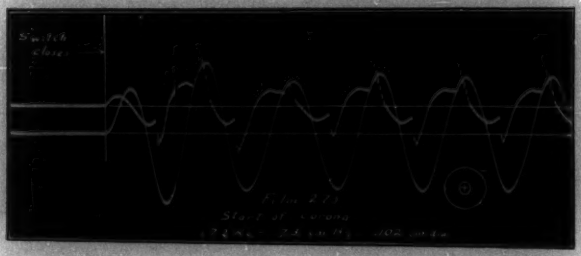
[BENNETT]

Fig. 231
Start of corona
340 volts
3 cm. Hg
102 cm. dia.

Fig. 232
Start of corona
621 volts
3 cm. Hg
102 cm. dia.

[BENNETT]


Switch close
Film 274
Start of corona
1572 K. 73 cm Hg
102 cm Hg


Switch close
Film 275
Start of corona
102 cm Hg

Film 277
377 K.

[BENNETT]

which these oscillograms were taken is so low that the charging current of the wire below corona causes a deflection of the current vibrator which is almost inappreciable.

At voltages slightly higher than the corona voltage the characteristic appearance of the current wave forms is shown by oscillograms 221 and 222. Copious ionization occurs for a short interval of time near the peak of the voltage during the half cycle in which the wire is cathode. There is no indication of copious ionization during the half cycle in which the wire is anode. After the cessation of ionization the current reverses and continues to flow in the reverse direction throughout the balance of the cycle. At higher voltages copious ionization also occurs during the half cycle in which the wire is anode, as indicated by the hump on the current wave form under the negative voltage peak on oscillograms 223 and 232.

Relation between the Air Pressure and the Corona Voltage. The relation between the air pressure and the impressed voltage at which the hump can just be detected in the current wave form of 0.102-cm. phosphor bronze wire is shown in Fig. 9. For the purpose of comparison, the values of the visual critical voltage for this conductor have been computed from the formula given by Peek for parallel conductors: These values are also plotted in Fig. 9, Peek's formula for the visual critical voltage e_v to neutral is

$$e_v = \left(1 + \frac{0.301}{\sqrt{r\delta}}\right) 29.8\, r\delta \log \frac{s}{r} \text{ peak kilovolts} \qquad (7)$$

The two curves agree at atmospheric pressures and at pressures of about two cm. of mercury; at intermediate pressures the discrepancy is as high as 13 per cent.

The Start of Corona on Switching. The observation that copious ionization persists with decreasing voltage to a voltage several per cent lower than the voltage at which it is initiated with increasing voltage, gives rise to some question as to what occurs in the first few cycles after suddenly applying to a wire a voltage high enough to cause corona. Is the ionization as complete in the first half cycle after closing the switch as after many cycles? Or does it "build up" over a number of cycles? With impressed voltages much higher than the corona voltage, one would expect to find the corona fully developed at least not later than the second half cycle. With impressed voltages only a few per cent higher than the corona voltage it is not improbable that the steady state may only be reached after several cycles.

The following oscillograms show the current wave forms immediately after applying the voltage to the wire. These oscillograms were obtained with the Fig. 2 connections modified as noted below. All switching was done in the primary of the step-up transformer; that is, the wire was permanently connected to the higher tension terminal of the step up transformer, the supply voltage was adjusted to the desired value, and the voltage

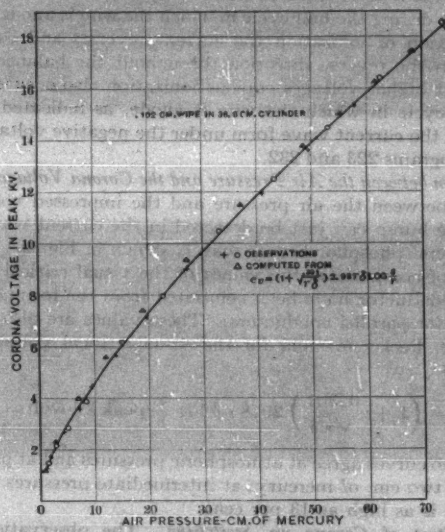


FIG. 9—RELATION BETWEEN AIR PRESSURE AND CORONA VOLTAGE

was suddenly applied to the wire by closing the main switch in the primary of the step-up transformer.

Oscillograms 230 and 232 were taken at an air pressure of 0.3 cm. of mercury, the former at a voltage about 12 per cent above the corona voltage. The potential vibrator and its series resistance was connected directly across the high-tension side of the step-up transformer for these oscillograms at low pressure. (For the switching oscillograms at atmospheric pressure, the potential vibrator was connected across the primary of the

transformer, as in Fig. 2). At these low pressures the positive current—from pipe to wire—is as large during the first half cycle as during subsequent cycles. The negative current, however, is low during the first half cycle and increases in value for the first eight cycles. This negative current does not necessarily indicate a current flowing in the primary from wire to pipe. It is probable that no appreciable current flows from wire to pipe, and that the apparent current in this direction is due to the interposition of the current transformer. That is to say, a unidirectional pulsating current flowing through the primary would account for the appearance of these films. The gradual increase of the negative current during the first few cycles may be attributed to the drift of the magnetic cycle in the iron to its permanent condition.

Oscillograms 273 and 275 were taken at an air pressure of 73 cm. of mercury, at voltages respectively 3 and 20 per cent higher than the corona voltage. An abnormally high voltage was invariably obtained on closing the switch; this causes excessive ionization during the first cycle and so masks the effect sought for at voltages only slightly higher than the corona voltage. The oscillations were damped out for oscillogram 273 by the use of the 0.94-megohm resistance in the primary of the current transformer.

Corona around a Rubber-Covered Wire. Oscillogram 277 shows the wave form of the charging current of a No. 14 B. & S. gage (diameter 0.16 cm.) single braided rubber-covered wire (diameter over all 0.55 cm.) at a voltage high enough to cause the formation of corona in the air around the insulation. This wire was mounted in the 36.8-cm. diameter wire mesh cylinder.

Note that the most striking oscillation in the current no longer occurs during the half cycle in which the wire is cathode, as with bare wires, but during the half cycle in which wire is anode.

IV—Summary

The features or characteristics of the corona around wires brought out by oscillograms of the charging and leakage currents may be thus summarized:

1. The distortion in the current wave form, which results from copious ionization at the time of the voltage peak, is observed simultaneously with the hissing sound and bluish discharge from the wire.

2. At air pressures below 20 cm. of mercury, copious ionization,—as indicated by the hump on the current oscillograms,—

sets in at a lower voltage during the half cycle for which the wire is the cathode than during the half cycle for which it is the anode.

3. From the oscillograms thus far obtained at atmospheric pressure it has been impossible to determine whether there is any difference in the voltage at which the distortion appears in the two half cycles, at pressures near atmospheric.

4. The boundary of the ionized region does not gradually expand outward from the wire with the increase in voltage during the half cycle. The loss of insulating properties in the air surrounding the wire must be conceived of as taking place with extreme suddenness. The evidence of this is the oscillation in the current shown on the oscillograms.

5. At air pressures near atmospheric, the asymmetry which results from the combination of the two conditions, namely, current carriers having different properties—positive and negative ions—and a field between unsymmetrical electrodes, manifests itself in two ways: (a) the loss of insulating properties by the air is much more sudden in the half cycle in which the wire is cathode, (b), at voltages slightly higher than the corona voltage, the power loss in the corona is greater during the half cycle in which the wire is anode. At higher voltages the percentage difference between the power loss during the two half cycles becomes extremely small.

6. At low air pressures, the asymmetry manifests itself as follows: (a) for a considerable range of voltages above the corona voltage copious ionization seems to occur only during the half cycle for which the wire is the cathode; (b) at these voltages the peak value of the current when the negative ions travel outward from the wire is far higher than when they travel inward toward the wire; the time of outward flow is, however, far shorter than the period of inward flow. Under these conditions, it is seen that the average values of the currents in the two directions may differ but slightly, while the root-mean-square values are greatly different.

7. At voltages above the corona voltage, copious ionization sets in at a lower voltage in the half cycle for which the wire is the cathode than in the other half cycle: in other words, copious ionization is initiated earlier in the cycle when the wire is cathode than when it is anode.

8. The quadratic relation between power expenditure in the corona and the impressed voltage, developed by other investigators for parallel conductors, is shown to apply to the single case of concentric cylinders for which the losses were obtained.

9. There is some evidence that several cycles may be required after applying the voltage for the conditions between concentric cylinders to reach a steady state.

10. A curve is plotted showing the relation between the air pressure and the voltage required to cause the distortion to appear in the current wave form.

DISCUSSION ON "THE ELECTRIC STRENGTH OF AIR—IV" (WHITEHEAD), "THE POSITIVE AND THE NEGATIVE CORONA AND ELECTRICAL PRECIPITATION" (STRONG), "LAW OF CORONA AND DIELECTRIC STRENGTH OF AIR" (PEEK), AND "AN OSCILLOGRAPH STUDY OF CORONA" (BENNETT), COOPERSTOWN, NEW YORK, JUNE 27, 1913.

C. F. Scott: The papers that have been presented are part of a series which have been appearing in our transactions, building up a new literature. It was, I believe, fifteen years ago when the first paper on this subject recorded a number of experiments and tests by Mr. Mershon on the lines of the Telluride Power Company, in Colorado, and the tests were made jointly by the coöperation of Mr. Nunn of that company, and Mr. Mershon and the company he represented. That paper presented the effect of these losses and the method of measuring them, and the success of the tests was largely owing to the ability and ingenuity of Mr. Mershon in meeting new requirements under particularly difficult conditions.

The large fact presented was that above certain voltages there was corona loss as it has since been named. Professor Ryan became interested and undertook a study of these laws and conditions, and in a year or two came a paper by him giving the results of his laboratory work. Presently Mr. Mershon presented results of other tests in the field. Others have taken up the investigation. The paper presented this morning is the fourth paper in a series, another paper is the third paper in a series by the respective authors, dealing with this subject. Fifteen years ago a new fact was presented, and a new field of investigation was opened.

In the meantime, power transmission has gotten up away beyond the early voltages, and these matters of corona have become very important engineering factors and engineering limitations. New methods and instruments, both theoretical and investigative, are employed. New knowledge, new physical theories, are here applied, and this wonderful instrument, the oscillograph, is now applied to this very remarkable condition of measuring the charging or corona current in a little wire a dozen feet long.

This Institute as a whole, the engineering profession, and this whole department of high-tension transmission, are very much benefited by these papers, and I think I can speak for all when I congratulate and commend the authors on the excellent character of the work and its importance, both from the theoretical and the engineering point of view.

L. T. Robinson: The details of the work that has been done here are of very great interest; they will become of more and more interest as time goes on. But we have now heard a great deal of this work, we have many records, and perhaps at this

time it would be possible to go back a little to give the work an important practical application.

The one particular point that seems to be involved here, indirectly, is the question of the measurement of voltages. We have here, apparently, another means that may be employed, that is the measurement of voltage by the appearance of corona before the disruptive discharge takes place, and in many instances I think that would be a very valuable thing. We have, of course, other methods that are applicable in perhaps the majority of cases, but if I read the paper of Messrs. Whitehead and Fitch correctly, there appears to be a very sharp point where the phenomenon is observable, and if it would not be leading this discussion a little to one side, I would like to have something said by the authors and by the other gentlemen present as to what would be the advisable procedure in the case of different voltages and different conditions which must be met.

Professor Bennett's work, in which he speaks of the small angles between the currents in the transformers, of the nature of a degree, is very good testimony of the care with which he has looked over his results, and he has drawn the line rather finely, but it is quite evidently there, when you come to look for it. If we may digress just a little more, for an instant, I think it is a thing that may be taken as an indirect lesson by all of us, that is, we do a great deal of work and make lots of diagrams and make many figures on paper, etc., and make a lot of observations, but we do not half look at these things. If we examined them more carefully, we would not need to take so many observations. The small transformer to make the current observation in the oscillogram has been used many times, but I do not think the possibilities of operating in that way have been brought out so that it is quite generally appreciated. It might be of interest to say that in an ordinary electromagnetic instrument, for instance, a moving iron instrument, there is required in the neighborhood of from two to five watts to operate the instrument. In the oscillograph, although the current is rather large, the total energy required is rather small, and, unless I make some mistake in multiplying it, it corresponds to about 1/400th of a watt, so that there is a possibility of doing a great deal with suitable transformers, and no doubt the transformers could be much improved, and would be well suited for any other purpose, and the necessary corrections supplied. Even a sensibility of 1/400 watt leaves a good deal to be desired, because when you come to another instrument, that is the moving coil instrument of the type first commercially developed by Dr. Weston, we have something like 1/1000th of a watt as necessary to send it across the scale.

J. B. Whitehead: Mr. Robinson's suggestion that we consider the corona as a measuring instrument is one near to my heart, but I will not try to divert the discussion that way for a moment, but will get back to it later, perhaps.

Alan E. Flowers: In regard to electrical precipitation of suspended particles from gases, it ought to be emphasized here, that the subject has a very respectable history in physics, and that we are particularly indebted to the physicists of England for the ground work of the subject. C. T. R. Wilson showed that water vapor tended to condense upon ions and so precipitate. Lodge showed that foggy, out-door air could be cleared in the neighborhood of highly charged electrical conductors.

Out on the Pacific Coast, Professor F. G. Cottrell has been working on electrical precipitation for several years and has obtained some very satisfactory results. About a year ago, Professor R. C. Carpenter described a settling chamber or room, fitted with baffle plates, where the gas velocity was so reduced that something like 98 per cent of the dust was removed. The electrical methods were, at that time, capable of removing about 93 per cent of the dust. These figures are only approximate and any error in their statement should not be attributed to Professor Carpenter.

I should like to have from Mr. Peek more explanation of the large values for the "critical distance", which increases as the square root of the radius, does it not?

F. W. Peek, Jr.: Yes.

Alan E. Flowers: So that with a sphere of 12.5 cm. diameter, the critical distance attains values of nearly one cm.

In Professor Bennett's paper, attention should be called particularly to the use of the term "hypothetical gradient" and the author given our thanks for the use of the term. It seems to me that the values obtained by calculation, which we have been in the habit of using, must be subject to large corrections under corona conditions.

Taking up the question of voltage measurements raised by Mr. Robinson, I would like to call attention to an article published recently in England by Milner. In high-voltage measurement, probably the greatest difficulty is that due to the effects of frequency.

Milner's work throws much light on this point. He used the Braun tube to investigate the relation between the voltage and current in a small sphere gap, carrying an oscillatory high frequency discharge. Instead of voltage-time and current-time curves, Milner thus obtained volt-ampere curves, from which, assuming a sine current, the time curves were calculated. In Fig. 1, are shown the resultant curves for a discharge, oscillating at a frequency of 2,000,000 cycles per second. The initial peak of the volt-time curve is about 3000 volts; the voltage then drops to the arc value of about 35 volts. Succeeding loops all show an inital value of 300 volts, corresponding to the glow value, followed by the low arc value of 35 volts. The current showed a damping intermediate between the linear and logarithmic rate. The variation of the effective resistance in the oscillatory circuit doubtless has something to do with this rate of decay.

The high initial value of 3000 volts was obtained only once in each wave train, but the 300-volt glow value was necessary in each alternation, being followed by the arc value of 35 volts. These voltages are the same as the values one is accustomed to in work at commercial frequencies.

It would seem that this work is at least an indication that we may use the breakdown of air between spheres as a measurement of voltage, independent of frequency. These results also show the tremendous rapidity with which the fully ionized condition disappears.

Professor Bennett mentioned that in any cycle, corona ceases at voltages of 2 and 3 per cent lower than the value at which it began and also, laid some stress on the possibility that antecedent ionization, either in the same or preceding cycles, had something to do with the critical voltage. From Milner's work, one would conclude that recombination is too rapid for antecedent ionization to affect the critical voltage.

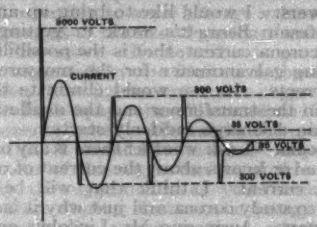


FIG. 1

On page 1790 and in the corresponding curves Fig. 7 it is shown that the voltage at which the corona begins in any cycle is appreciably lower, when the voltage is much in excess of the critical value. It might be pointed out that this, as well as the lower voltage for cessation of corona in any cycle, might with greater probability be ascribed to the temperature of the electrode surface. The bombardment of the surface being such, as to raise appreciably the temperature of a very thin surface film.

I would also like to ask Professor Bennett why the polarity, giving the greater power loss, is not the one allowing the breakdown at a lower voltage.

J. B. Taylor: It is interesting to note that Prof. Bennett has made use of a method which I suggested several years ago, though I believe Prof. Bennett has been the first to show records obtained by using it.

I refer to the differential connection of a current transformer in which the charging current, due to electrostatic capacity of

the wire on which corona is being studied, is balanced out by a condenser of proper capacity.

The construction of the balancing condenser should be such that it is free from corona. This leaves the corona current alone for recording or noting in instruments such as the oscillograph, ammeter, and wattmeter or other device.

I wish to ask if the doubling of the potential waves as shown in records 179 and 180 has any special significance, or does it result merely from a double exposure obtained accidentally in making the records.

W. H. Pratt: I am very glad Mr. Robinson raised the question as to the adaptability of methods of using corona for measuring high potential. It is a matter I have had in mind for some time and was hoping to hear at this meeting some facts which would either confirm or else change my opinion as to the possibility of making use of this phenomena in this measurement. I have nothing in detail to suggest, but would like to hear if there are others who have any ideas on that subject.

Alan E. Flowers: I would like to bring up another point, in regard to Professor Bennett's work in getting oscillographic records of the corona current, that is the possibility of using the Einthoven string galvanometer for the measurement of these very small currents. Its use would eliminate the difficulty of self-induction in the transformer and the oscillation that occurs when the corona discharge suddenly starts.

Paul M. Lincoln: I ask whether there is any one here who has made or observed or knows about the current of corona for high-voltage direct current. I think that will be an extremely favorable way to study corona and just why it is.

Alan E. Flowers: Answering Mr. Lincoln's question, I recall that Watson presented a paper at the Winnipeg meeting of the British Association for the Advancement of Science, in 1909, published in the *Electrician*, Vol. 63, page 828, Sept. 3rd, 1909. In this paper, experiments were described giving values of the corona current with direct current at voltages up to 100,000 volts. The critical voltages were the same as those found by Ryan for the maximum instantaneous alternating current voltages, when using the wire and concentric cylinder. For parallel conductors, out doors, under atmospheric conditions, much lower values were found and the critical voltages corresponded much more nearly to those found by Mershon at Niagara.

Paul M. Lincoln: What is the order of the losses which occur in that manner in comparison with those which occur in the breakdown with alternating current?

Alan E. Flowers: I do not recall the figures for the losses, but my impression is that the losses were of the same order as with the alternating current, though smaller.

John B. Taylor: I think Mr. Lincoln's point is very pat, and there is something wrong in the formula which puts frequency

directly into the formula. When we come to direct current the frequency should be taken as zero, and there is either a different set of conditions found to obtain or the formulas must be regarded as approximate, to be used only within a limited range of frequency.

Paul M. Lincoln: That is the object I had in mind in asking for the order of the losses with direct current. I thought probably the loss which would take place if the voltage were established on the wire and kept constant, compared to the loss which is due to the initial breaking down of the film is so small as to be entirely masked at frequencies of 60 cycles or thereabouts. That would lead the ordinary observer to believe that frequency enters directly as a factor, whereas as a matter of fact, at very low frequencies there is an appreciable loss.

John B. Whitehead: Before answering the one or two questions which have been asked specifically as to my paper I want to make one or two comments of my own on the papers of the other authors.

I want to call attention to some average values that are given by Professor Strong as to the size of gaseous ions and the velocities with which they move. If one wishes to get a conception of the mechanism suggested by the ionization theory for the conductivity of gases, these figures are rather suggestive.

Passing to Mr. Peek's paper, he will excuse me if I take another crack at his "energy zone." He knows there is nothing but good feeling in this. I should like to know why it is necessary to go to the extent of the suggestion he makes. If I understand it properly, the suggestion is, as you increase the voltage on the line, you are storing electrostatic energy in the electric field, and there finally comes a time when the medium immediately around the wire cannot stand any more energy. That is all right as far as it goes, but the thing which entirely robs the suggestion of any interest to me is that there is nothing constant about either the volume, density or length over which the discharge takes place, in other words, the zone is different in length for every size of the wire. That brings us back to where we were before.

I am particularly glad to read Mr. Peek's observations on pressure. I believe it is the first time they have been published in detail, and they, of course, offer a very interesting substantiation of the relation which he has given connecting the critical gradient with the density.

I also find that Mr. Peek is adopting the language of the ionization theory. At the top of page 1774, he suggests the mechanism by which the corona may be started, and that there may be free ions at the surface of one of the conductors. It is not necessary to assume that there are any ions at the surface. There are always a number of free ions in the air owing to the continual state of upsetting and recombining of the ions in the molecule. In normal air there are about 1000

free negative ions per cu. cm., and the number may increase four or five times under certain conditions. It is possible to increase the number enormously by various ionizing agents. When a difference of potential exists between conductors these ions are put in motion by the electric field. They are free charges and move in the direction of the gradient.

Passing to Prof. Bennett's paper, I want to express my very great admiration for the care with which the experiments have been performed and to state that I regard it as one of the most valuable contributions to this subject which we have had in some time. There are some points I want to raise in connection with it. On page 1784, in differentiating between the instant of ionization and voltage of copious ionization, the suggestion is made that there is some ionization due to the electric field before the instant of copious ionization. With the very sensitive method for observing the presence of ionization with the electroscope, I have never found the least evidence of any ionization preceding the actual instant of copious ionization.

Prof. Bennett says: "The hump is first detected during the half cycle in which the wire is anode and the cylinder cathode." If the wire is anode, the negative charges are moving in towards it and they are consequently moving into a region of intense field, and they will be accelerated more rapidly during their mean free path. This is in accord with the theory of secondary ionization. During the time which elapses between two collisions with molecules, if the ion has moved into a more intense field, it acquires greater velocity than if it had moved the opposite direction. Prof. Bennett points out that he was unable to observe this on the records, and refers to oscillogram 183. Oscillogram 183 appears to me to substantiate his statement. That oscillogram is as I would expect to find it, and I do not see any evidence on it of a starting of corona on the other half of the wave, when the wire is cathode.

Referring to page 1786, when slowly lowering the voltage, reference is made to the fact that the hump does not disappear from the current wave at the same voltage at which it began. I venture to suggest that this may be explained as a temperature lowering. The appearance of corona is sensitive to a change in temperature. The actual presence of corona, representing energy expenditure, elevates the temperature of the gas in the neighborhood of the wire. We have found through a long series of observations a number of discrepancies for which we could not account until we finally traced it to the elevation of temperature of the wire due to slight rubbing for cleaning purposes between observations. We found by letting it stand three or four minutes, to be sure that the whole apparatus came to constant temperature, that the trouble disappeared.

In paragraph 5, Prof. Bennett says that the oscillation in the current occurs when the wire is cathode to the cylinder. If the wire is anode in the neighborhood of starting of corona, the corona

is confined to a comparatively small region. When the wire is cathode, and you have the actual process of ionization or copious corona, you have a more free generation of ions due to the fact that the whole region is largely broken down, and so has high conductivity.

In paragraph 2, on page 1789, Prof. Bennett says: "With increasing impressed voltages, the instantaneous voltage at which the copious ionization sets in becomes smaller and smaller," and then refers to Fig. 7 to show the amount of that reduction. I am not sure that the temperature would account for as great lowering as he observes, but I want to suggest, at least, that it may be a possible explanation. It is extremely important to look for temperature variation.

At the top of page 1790 a statement is made: "The current is quite appreciable before the start of copious ionization." I venture to suggest that this is a residual effect, due to the foregoing corona. Recombination goes on with enormous rapidity, as indicated by the fact that the corona does stop. But this does not mean you have no ionization; the process of ionization is stopped, but there are plenty of free ions left and they constitute the current indicated by the slight accent in the curve of film 188.

Coming to page 1793, with reference to the great difference in the losses in concentric cylinders and parallel wires, I think the explanation is obvious,—This process of loss to my mind is made up of two factors, one is the process of ionization, or breaking down of the molecules, which undoubtedly requires energy. The other and larger part of the loss is due to the actual conduction current, caused by the passage of ions from one conductor to the other.

L. T. Robinson: Does not the loss vary directly as the frequency?

John B. Whitehead: I do not believe it varies directly. The difference in the paths of the ions in concentric cylinders and in parallel wires, would account for the difference in loss observed by Prof. Bennett. In the concentric cylinders you have perfectly straight paths for the ions, and very much shorter than in the widely scattered paths which approximately follow the electrostatic field between parallel wires. The actual loss must vary in some way with the frequency. If you get a breakdown on every wave, you pile up the loss with increasing frequency, but I do not believe there is a strictly proportional relation.

In regard to Mr. Robinson's suggestion as to measurements. In our laboratory we have been conducting experiments for the perfecting of the wire and cylinder apparatus as measuring instruments for some time, and I hope to be able to present the results of that investigation to the Institute in the near future.

The accuracy with which one can repeat observations on the formation of corona on a clean wire in a cylinder is very much closer than the possible control of the usual alternating-current

circuit. There is no question in my mind that if we can reduce the apparatus to a convenient form, so that it may be carried about, we have an instrument which is incomparably better, as regards final accuracy than either the needle or the sphere gap. A serious limitation of such an instrument is that for a given voltage there is only one size of wire. If several different voltages are to be measured with the same apparatus a number of wires are necessary. However they may be inserted readily and frequently, in a clean condition, corresponding to different voltages and I have not found that this is a serious complication. We have an apparatus, comparatively limited in range, as yet, with which we have worked for some time. Taking voltages almost daily since the first of October last year, and correcting for temperature and pressure, we have had no difficulty in checking these voltages over a wide range of conditions to a fraction of a per cent.

We are also investigating the surfaces of metals, as regards their permanency, looking to the possibility of eliminating the necessity for cleaning. We have not got far enough along with this to say what the best material would be. We are also trying various wave shapes, as the voltages measured have so far been considered, and I believe properly, to be the peak voltage, the highest voltage on the wave.

There is another limitation to such an instrument, that I regard as perhaps more serious than any and that is the fact that the observing instrument which so far has been found to be the most suitable for the observations is the electroscope, and the electroscope, unfortunately, is not a convenient instrument to carry about. It is not suitable for a shop test of high voltage. It is obviously impossible to use the visual appearance of the corona as the measuring instrument. To do this a room absolutely dark is needed and one must be in the room several minutes before he can see the first appearance of corona. We have developed another method of detecting the beginning of corona. We punch the outer cylinder full of small holes, and surround it with another cylinder so connected to the cylinder which forms the grounded side of the circuit as to make it sound-proof. Two openings in the outer cylinder are connected by two broad rubber tubes to two ear pieces strapped over the head. You can hear the corona start in a quiet room, and fix the point at which it does start on a clean wire just as closely as by looking at it. We have checked this with many tests made by two independent observers. I believe there are great possibilities in the concentric cylinder apparatus as measuring instrument.

I would like Mr. Flowers to give the references to Milner's paper and tell how these interesting curves at two hundred million cycles were traced.

With reference again to Mr. Lincoln's question as to experiments with high-voltage direct current, Watson's observations

were made with the induction static machine as the source of voltage, and while his observations were extremely interesting, I believe they are qualitative rather than quantitative. I do not think there should be any difficulty, however, in understanding the loss at continuous voltage if you go back to the idea which I have suggested, and which I think is unquestionably so, that a large part of this loss, not the principal part of it, is due to the actual passage of current between conductors.

Paul M. Lincoln: If the conception which Dr. Whitehead has just given is correct, our law of loss due to heating needs revision. Frequency does not apply there.

F. W. Peek, Jr.: Answering the questions asked in reference to variations of corona loss with frequency: The greater part of the loss over the commercial frequency range is a per cycle loss or varies directly with the frequency. There is also added to this a small constant loss independent of the frequency.

The complete loss equation may be written:

$$p = k\ (f + a)\ (e - e_0)^2 \text{ kilowatts per kilometer of circuit.} \qquad (1)$$

Then at zero frequency f becomes zero and the loss is

$$p = k\ (a)\ (e - e_0)^2 \text{ kilowatts per kilometer of circuit} \qquad (2)$$

The constant a is comparatively small.

Therefore where f is comparatively large a becomes negligible and the loss may be written:

$$p = k\ f\ (e - e_0)^2 \text{ kilowatts per kilometer} \qquad (3)$$

The equation is generally written in the form (3) for convenience in working at the higher commercial frequencies near 60-cycles and practical size of conductors. When I first gave this equation in my paper in 1911* I stated it did not mean zero loss on direct current. The zero frequency loss indicated in (2) is not necessarily the d-c. loss, but one would expect the d-c. loss to be higher. There must be loss on the d-c. because as soon as a given flux density is reached the air must break down. This requires an expenditure of energy. There must also be a flow of energy to keep the air in this broken down state as the ionized particles move away. Some three or four years ago I made some measurements of corona loss on a wire in a tube. I found that if air were sent through the tube the loss increased with increasing air velocity. The faster the broken down air was moved away the greater the loss.

Watson has made loss measurement of d-c. corona on wires. While these loss measurements are rather qualitative than quantitative, they indicate a d-c. loss of about $\frac{1}{4}$ to $\frac{1}{2}$ the 60-cycle a-c. loss at the same maximum voltage.

I have frequently used corona as a means of measuring very high voltages as a check on other methods.

*Law of Corona, TRANS. A. I. E. E., Vol. XXX, 1911, p. 1889.

Sometime ago I found that the needle gap varied a great deal from time to time at constant temperature and pressure. This variation is caused by humidity. Around the needle gap there is a great brush discharge before spark-over. The water in the air which exists as a gas is probably changed into vapor or a "fog" around the needle points by the brush discharge. This has the effect of increasing the size of the conductors and causes a higher spark over voltage. Humidity has no effect on the starting point of corona, or spark over on spheres, because there are no brushes to cause change from gas to vapor. I mention this because it has a bearing on precipitation.

Prof. Bennett's loss investigation confirms the "quadratic law" which was first derived by me in 1910, and given in discussions in Jan. 1911 and more completely in the "Law of Corona," June 1911. The difference is quantitative. This is because of the small size of wire used, which is much smaller than any used on commercial lines. Where the wire is smaller than about 0.25 cm., e_0 is larger than that expressed by the simple practical equation, and I have given a more complete equation to cover small wires. This complete equation, however, is of theoretical interest.

For use over a wide range of frequency and radius of conductor, it is:

$$p = 241\,(f + 25)\sqrt{\frac{r + \frac{6}{s} + 0.04}{s}}\,(e - e_d)^2\,10^{-8}$$

$$e_d = g_d\, m_0\, r \log_e \frac{s}{r}$$

$$g_d = 21.2\left(1 + \frac{0.3}{\sqrt{r}}\,\frac{1}{1 + 230\,r^2}\right)$$

Even before the practical size of conductor is reached, $g_d = g_0$ and is constant, or e_0 is constant for all practical sizes. For the smaller sizes g_d increases and finally at zero radius $g_d = g_v$. Prof. Bennett's data should check substantially the above equations.

These equations derived from measurements over a frequency range of 20 to 130 cycles and wide conductor range reduce to (3) for practical size of conductor, spacing, and frequency.

It must always be remembered that there should be no loss below e_v with perfectly smooth conductors. The loss below e_v therefore varies from day to day depending upon irregularities and follows the probability curve. It is not of much practical importance to know this loss, as the storm loss limits the maximum voltage to about fair weather e_0.

In regard to Dr. Whitehead's objection to the energy zone

theory: This theory has helped me in deriving formulas and has therefore been useful. For instance—I probably would not have been able to write the formula connecting visual gradient with radius and pressure if I had not looked upon it in that way. The electron theory is of a great help and will be a greater help, but it is not possible to explain everything by it at the present time.

Edward Bennett: With reference to the question about the double appearance of the voltage curve on films 179 and 180, I would say that is due to a fault in the reproduction of the film. The curve is rather broad.

The use of the string galvanometer has been suggested because it has been assumed that the resistance of the current transformer is excessive. By reference to Fig. 3, however, it will be noted that the resistance of the current transformer and vibrator is only 0.02 megohms, whereas the capacity-reactance between the wire and cylinder in series with which it is connected is 90 megohms, so that the voltage consumed in the current transformer will be a small fraction of one per cent of the total impressed voltage. It is true that the current sensibility of the string galvanometer is extremely high, but it must be remembered that the current sensibility has been obtained at the expense of a long period of vibration, so that the string galvanometer would be absolutely unable to reproduce frequencies of the order we have to reproduce in this case.

With reference to the statement during the discussion that film 183 shows the distortion in the current wave form only when the wire is anode, I would state that it is extremely difficult to detect in the reproduction any distortion in the current wave form during the half cycle when the wire is cathode, but such a distortion can be readily determined on the original films.

John B. Whitehead: It shows here on the reproduction of the film when the wire is anode and not when the wire is cathode.

Edward Bennett: The difference between the appearances of the distortions in the current curves, which makes it difficult to determine whether there is a certain range of voltage over which the distortion occurs only during the half cycle when the wire is the anode, or vice versa, is pointed out in the discussion of film 183.

John B. Whitehead: The only point I want to make is if you have that kick in the current wave, its amplitude is much greater than the amplitude of the disturbance on the other side. It indicates to me if you carry the voltage on down it would simply show the fact on the film as it is shown here.

Edward Bennett: I do not think that necessarily follows, when you consider the other fact developed by the oscillograms, namely, at higher voltages copious ionization starts earlier in the cycle when the wire is cathode than when it is anode. The

direction of the gradient when ionization is first observed, is still, I think, an open question.

With reference to the method of measuring voltages by means of corona, I understand that Professor Ryan has done a great deal of work in which he uses a measuring instrument comprising a conical conductor in a concentric cylinder. This is the only type of instrument with which it would be feasible to measure varying voltages. Suppose you wanted to determine the peak voltages due to surges, etc. It is not feasible to change the inner conductor, as has been suggested, but a conical inner conductor may be used and the point on this conductor at which the corona terminates may be noted. Whether this can be used as an exact indication of the highest voltage, remains to be determined.

It is my understanding that all the equations expressing relation between loss and voltage, between the critical gradient and radius of conductor, etc., are not rigorously exact but are approximate equations.

Messrs. Whitehead and Peek are to be congratulated upon the manner in which they marshalled and analyzed a very large mass of experimental data, and from this have evolved the few elegant relations embodied in the equations expressing the interrelations between power loss, diameter of conductor, air pressure, and impressed voltage. The extension of these empirical relations between the critical intensity, the density factor and the diameter of conductor, which were first worked out for the case of cylinder conductors, to the case of spheres, is a distinct contribution to the subject.

In addition to this contribution the third paper is entitled "A theory of rupture." This theory is advanced in the attempt to account for a discrepancy between our preconceived notions and experimentally determined facts. The preconceived notion is that the computed electric intensity or gradient at which a gas gives experimental evidence of breaking down ought to be a constant. The fact is that the computed gradient, the gradient computed on the assumption that there is no accumulation of charge around the conductors is not a constant, but becomes larger and larger for conductors of smaller and smaller diameters.

After developing the simple relation $g_s = g_0 \left(1 + \frac{k}{\sqrt{r}}\right)$ and noting from this that the computed gradient is always constant and equal to g_0, at a distance of $k\sqrt{r}$ from the surface of the conductor, the simplicity of the relation seems in some way to lead to the conclusion that failure does not occur at the surface, but only after "rupturing energy" has been stored around the wire in a zone between the wire and this hypothetical cylinder at which a constant hypothetical gradient is obtained.

It must be remembered that an analytical expression can be found which will express the distance between the surface of

the conductor and the point at which the computed gradient at the voltage of rupture has any other constant value, as 25 or 20 kilovolts per cm.

Does this fact, however, the fact that an expression can be found for the distance from the surface of conductors to a point where the computed gradients are constant, warrant the interjection of the notion of an energy storage zone? It must be recognized that in the hands of the author of the theory, the notion of the energy storage zone has been very fruitful and has led to some very simple relations, but in the hands of others, or in the mental processes of others, of whom I am one, the notion of an energy storage zone is absolutely fruitless and barren. This may be a fault, not in the notion, but in the mental processes of those to whom the notion is fruitless. To me it is an incident that the expression for the distance between the surface of a conductor and the point at which the gradient is 29.8, or 31, or 33.6 kilovolts, assumes a simple form. I have no real quantitative explanation to offer for the relations observed, but in my estimation the fruitful explanation will be based upon statistical relations to be expressed in the language of the atomic structure of electricity.

Alan E. Flowers: The article by Milner was published in Nov. 1912 in the *Philosophical Magazine*, Vol. 24, page 709.

John B. Whitehead: How was that curve obtained?

Alan E. Flowers: Results were obtained by the use of the Braun tube and the sharply defined cathode ray pencil, produced by having two metallic screens, each pierced by a small hole in the center and along the line of the axis of the tube and also perpendicular to the cathode surface, the screens also forming anodes in the tube. Part of the cathode rays, proceeding in a direction normal to the cathode surface, passed through these

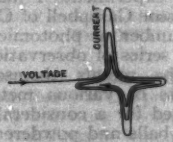


FIG. 2

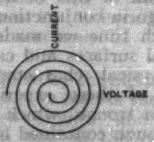


FIG. 3

two holes and were deflected by the magnetic and electric fields of the discharge circuit. The oscillating current through the sphere gap was assumed to be a sine wave and was produced by an induction coil. The primary on this induction coil was in series with the primary of another coil, whose secondary supplied the discharge in the tube, thus making the cathode ray pencil occur in synchronism with the current in the gap circuit. The oscillating current through the gap passed also

through a coil whose axis was at right angles to the tube and "cathode ray pencil" and produced a magnetic field tending to deflect the cathode pencil vertically. Plate electrodes so set that the electric field between them tended to deflect the cathode pencil horizontally, were connected either across the sphere gap or across the supply condensers and consequently deflected the pencil in proportion to the gap voltage or the total voltage of the oscillating circuit. The cathode pencil fell upon a willemite screen and was photographed. In this way, crossed and spiral curves were obtained, such as are shown in Figs. 2 and 3. The photograph showed rather a wide band. A line was then drawn along the middle of the photograph trace and this line-curve analyzed to give the curve shown in Fig. 1 (p. 1813). The actual record is thus the volt-ampere characteristic, from which, assuming a sine current, the time curves may be calculated. The volt-ampere characteristics obtained when the total oscillating voltage was used, were of spiral or elliptical form, thus checking the assumption of the sine wave discharge.

John B. Whitehead: The Braun tube is perfectly well known.

Alan E. Flowers: This method of getting a volt-ampere curve is, however, new, and gives extremely useful information under the very difficult conditions of extremely high frequency.

William J. Hammer: Professor Whitehead referred to the effect of particles of dust, on the path of the flow; and he also referred to some experiments conducted on the surfaces. It seems to me that the surface characteristics of metal is a matter to which not sufficient attention has been given, where particles may rest on the surface, where the surfaces are irregular or vary in their constitution or formation, or are exposed to effects of oxidation.

I speak of this because of some experiments I made some years ago in conjunction with Professor Campbell of Columbia, at which time we made a large number of photomicrographs of metal surfaces and carried out a series of observations upon the physical characteristics of the metals themselves. In certain of these experiments sheets of various metals were put in a trough, which was oscillated for a considerable time. This trough contained lignum vitae balls and powdered pumice stone and the surfaces of the metals were roughened slightly, but very evenly, and many photomicrographs were then made and studied. Many experiments were made upon these metals to show their surface characteristics. As an illustration, I will mention one of these experiments made upon aluminum and zinc. I poured a little collodion on the two surfaces, and as soon as it dried, the collodion peeled off the zinc but it stuck so fast to the aluminum I could not get it off with a penknife blade. There were many other experiments made at the time which were of a good deal of interest and demonstrated that these

surface characteristics of the metal itself are frequently very important.

John B. Whitehead: It has been known for some time that the corona-forming voltage does not vary at all with the material of the conductor. However, the condition of the surface of the conductor does have a great deal to do with the accuracy and sharpness with which the corona will appear with increasing voltage. Anything in the nature of a dust particle or surface inequality is capable of upsetting the observation. With the visual observation you can usually detect a surface imperfection as a slight brush discharge before the whole uniform corona breaks out. We have studied different surfaces, to find out which are the most permanent as regards oxidation or any other process which may upset the character of the observation.

Harris J. Ryan (by letter): As a contribution to the discussion of Professor Bennett's corona paper, Fig. R1 is submitted. It is the cyclogram in Fig. 6, page 545, Vol. XXII of the 1903

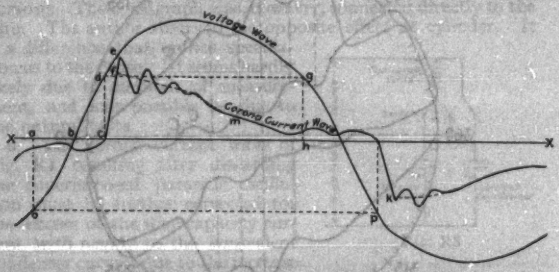


FIG. R1—DEVELOPED FROM CYCLOGRAM FIG. 6, PAGE 545, VOL. XXII, A. I. E. E. TRANSACTIONS

TRANSACTIONS. This cyclogram was taken by the method specified as number 1 in the present paper, *i.e.*, the coils of the cathode ray cyclograph were "connected between the wire" and the high-tension transformer which charges the wire in the concentric wire and cylinder outfit. The following items taken from this cyclogram are in substantial agreement or non-agreement with corresponding items in the paper:

1. The characteristic polarity difference in the wave forms of the corona currents when entering and when leaving the wire as discovered by Professor Bennett is here quite in evidence and in complete agreement with oscillogram No. 189. Thus it is known that the upper half wave was formed when the wire was negative and the lower half when it was positive.

2. The voltage required to start corona was 17.5 per cent greater when the wire was positive than when it was negative.

3. It shows that the wire positive, exceeds the wire negative

duration of copious ionization by 12.5 per cent and that the rate of such negative copious ionization is 62.5 per cent in excess of the rate of positive copious ionization.

4. That the impact oscillation superimposed upon the corona conduction current circulates only in a local circuit, is established by the following facts that appear in the original composite cyclogram reproduced in Fig. R2. The cyclogram *LC* records the composite condenser and corona conduction current passing between wire and cylinder. The cyclogram *CC* records the charging current through a non-corona-forming air-core condenser of equivalent capacity connected in multiple with the wire-to-cylinder condenser. The difference between these two

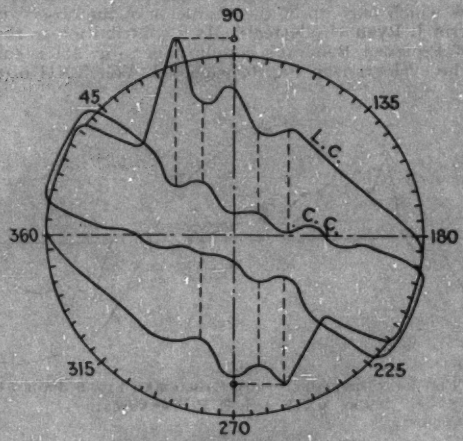


FIG. R2

is the corona conduction current transferred to rectangular coordinates in Fig. R1. Each cyclogram in Fig. R2 records a damped oscillation. These oscillations are seen to occur simultaneously, to have about equal magnitudes and to be in phase apposition. The scheme of connections used for the wire-to-cylinder and control condensers, the cyclograph coils and their switch to throw them in series with either condenser, is given in Fig. R3. It is seen at once that a local circuit is always formed through the corona wire and control condenser C_1 and C_2 and the cyclograph coils; it is seen also that when the coils are switched from the wire to the control condenser they are reversed with respect to this local circuit, though they remain direct with respect to the supply voltage. Under these circumstances

the same current circulating in this local circuit would necessarily be recorded in the line circuit through C_1 in one phase and that through C_2 in corresponding phase apposition. Since this is precisely what appears in the cyclograms of Fig. R2, those oscillations therein are one and the same. It follows, therefore, that the same process that subtracts the equivalent or control condenser current from the total corona-condenser current to the wire, isolates the sum of *once* the corona current and *twice* the impact oscillation, current. Is not this the case also in the author's oscillograms such, for example, as No. 189? The frequency of this oscillation is 2500.

5. This cyclogram shows clearly a continuation of the corona conduction after the collapse of the corona envelope and while the voltage wave is passing through zero. In many cyclograms made with conditions differing widely, substantially this same thing was always observed. See cyclogram samples hereof in Figs. 5 and 6, pp. 116 and 117, Vol. XXIII of the 1904 TRANSACTIONS. The cyclograph was, however, connected directly to the wire. The author observed the opposite effect at cylinder. It is a difference that invites speculation as to the cause. It seems hardly likely due to methods of measurement, and may possibly be due to the natural facts.

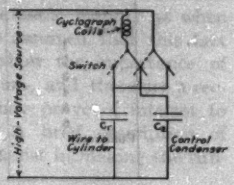


FIG. R3

6. The corona current wave of Fig. R1 resulting after discarding the superimposed parasitic oscillation must be further corrected for the excess of the wire capacity current with respect to the equivalent condenser current due to the increase in the capacity of the wire-to-cylinder condenser during the existence of the conducting corona envelope covering the wire. This is not a large correction and as yet our knowledge is not sufficiently complete to apply it with exactness.

7. Ten years ago we did not know about the importance of cleaning the wire to get consistent results. Consequently we obtained the sharp, sudden, copious ionization recorded in Fig. R1 only at the outset when the wire was "clean." In a series of studies extending over six months the wire was never cleaned. The cyclograms taken and preserved in the latter stages of this work all show a much more gradual start and formation of the copious ionization.

8. With the aid of the cathode ray power oscillograph, using electrostatic control only, in which all material self-induction is absent, I have often in recent years made a direct study of corona phenomena on short high-voltage lines and have never found any evidence of the presence of these oscillations. See a sample set of such corona power cyclograms in Fig. 6, p. 1096, Vol. XXX of the 1911 TRANSACTIONS. Nevertheless we must not fail to realize now the great importance of Professor Bennett's

discovery. Certainly we have in this new truth a clear indication of what we must expect to find in an open-ended 150-mile transmission line subjected to heavy corona at the middle*. Again it is hereby made evident that any corona-forming over-voltage to which a transmission may be subjected accidentally can become a source of high-frequency effects that we find are always hard on insulators subjected also to corona, for at high frequencies such coronas are extremely hot and most effective for puncture or fracture.

9. In reference to the happy distinction drawn by Professor Bennett between hypothetical and actual gradients, I have tabulated below the voltage duties of the individual units in a six-unit suspension insulator string supporting a No. 0000 B. & S. gage line cable, 3.5 feet from the ground, so that corona could be

No. of insulator units	Total voltage to ground	
	54,000	100,000
	Per cent of total	Per cent of total
Ground		
1	11.7	11.7
2	11.7	11.7
3	13.3	21.6
4	22.0	15.0
5	22.3	21.6
6	19.0	18.3
Conductor		
	Total 100.0	100.0

started on such cable at about 63,000 volts to ground, altitude 3900 feet, and developed in profusion when this voltage was raised to 110,000. Such voltage duties are given for the sub-corona voltage of 54,000 and the high over-critical corona voltage of 100,000.

Several tests of this sort were made. Always corona was observed to modify the original form of the field, *i.e.*, to change the hypothetical gradient. It should be said that the insulator units did not develop appreciable visible corona at the upper voltage, with the following exception: unit No. 6, next to the line conductor, showed a very faint glow visible in full darkness on the under side adjacent to the "pin". The line conductor was, of course, ablaze with corona. The measurements, although made by methods in which we have had little experience as yet, are believed to be substantially correct.

*E. L. West, *High-Voltage Line-Loss Tests*, A. I. E. E. TRANSACTIONS, Vol. XXX, 1911, p. 77.

A paper presented at the 28th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 9, 1913.

Copyright 1913. By A.I.E.E.

EFFECTS OF ICE LOADING ON TRANSMISSION LINES

BY V. H. GREISSER

In a number of papers on transmission line subjects, which have been presented before this Institute, mention has been made of the fact that wires hung from suspension insulators did not maintain their position in the same manner as when pin type insulators were used. It is assumed that this fact has not been sufficiently covered to show the importance of such change of condition of equilibrium, and therefore a record of actual experience and tests may prove of interest to engineers and operating companies. A brief description of the tower line experimented with will assist in making the subject clearer.

In the latter part of 1911, The Washington Water Power Company, of Spokane, Washington, finished the construction of, and placed in service, a double circuit tower line about 28 miles (45.1 km.) long, between its Little Falls power station and the high-tension, step-down substation near Spokane.

The type of tower used is shown in Fig. 1, and it is to be noted that the conductors on each side of the tower were spaced seven feet (2.13 meters) from each other in a vertical plane. Each conductor was a nineteen-strand, 270,000-cir. mil (136.8 sq. mm.) aluminum cable. Two ⅜-in. (0.953 cm.) diameter extra galvanized Siemens-Martin steel cables were attached to the top of the towers for lightning protection, and it was interesting to find, during tests on a tower, that these cables also have a very great effect in adding stability to the construction of the line as a whole. Each cable was suspended from the ends of the crossarms by means of four 10-inch (25.4 cm.) diameter insulator units as shown in Fig. 2, the length of the

complete insulator and cable clamp being 34½ inches (87 cm.) from the center of cable to the eye at the end of the crossarm.

The cable clamp (also shown in Fig. 2) consisted of two pieces of treated hardwood with companion grooves in which

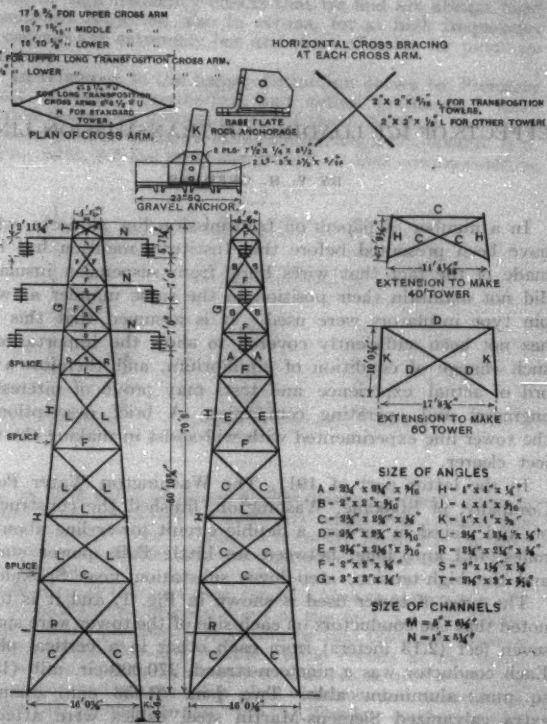


FIG. 1—STANDARD TOWER.

the cable was clamped as shown in the drawing, the hardwood being used in contact with the aluminum, to prevent any abrasion after the clamp was tightened.

An arcing rod ¼ in. (0.635 cm.) square was placed in a groove

on the upper side of the top half of the wooden clamp, this rod being intended to act in protecting the cable in case an insulator flashed over. There have been so few of such insulator flash-overs up to this writing that no extended data are available as to the usefulness of the arcing rods, but in the cases in which flash-over occurred, the cable was protected from in-

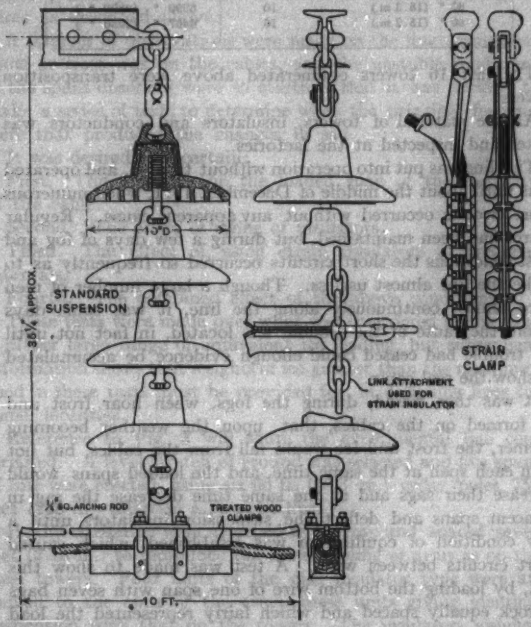


FIG. 2

jurious pitting or burns. A small strip of sheet aluminum was used to connect the cable to the metal parts of the clamp and lower insulator unit to prevent burning or digesting of the wooden parts.

The standard span was 750 feet (228 m.), but in 26.52 miles (42.7 km.) of actual tower line, 225 towers were used, making an average of about 625 feet (190 m.).

The heights of towers, weights and number used were as follows:

Height to lowest suspension from ground stub	Number used	Weights without footing
40 ft. (12.2 m.)	10	4315 lb. (1960 kg.)
50 " (15.2 m.)	189	5324 " (2420 ")
60 " (18.3 m.)	10	6390 " (2890 ")
50 " (15.2 m.)	16	6467 " (2930 ")

The last 16 towers enumerated above were transposition towers.

All the material of towers, insulators and conductors was tested and inspected at the factories.

This line was put into operation without trouble, and operated thus until about the middle of December, 1911, when numerous short circuits occurred without any apparent cause. Regular patrol had been maintained, but during a few days of fog and frost conditions the short circuits occurred so frequently as to make the line almost useless. Though a large number of men were almost continuously along the line, it was some days before the cause of the trouble was located, in fact not until the trouble had ceased could enough evidence be accumulated to show the real cause.

It was then found, during the fogs, when hoar frost and ice formed on the cables, that, upon the weather becoming warmer, the frost and ice would fall from the cables, but not from each span at the same time, and the loaded spans would increase their sags and at the same time decrease the sag in adjacent spans and deflect the suspension insulators until a new condition of equilibrium was established, which caused short circuits between wires. A test was made to show this fact, by loading the bottom wire of one span with seven bags of rock equally spaced and which fairly represented the load of ice that had been known to accumulate upon the cables.

The effect upon the loaded span and the adjacent spans was rather startling, since the loaded span sagged down to within 13 ft. (3.96 m.) of the ground, the increase in sag being approximately 20 ft. (6.1 m.) in a span 733 ft. long (223 m.).

The bottom cables of unloaded spans at either side became more taut, and thus reached a position within two inches (5.08 cm.) of the middle cable at the centers of those spans, the middle

cables being normally seven feet (2.13 m.) above the bottom ones.

The insulators supporting the loaded span were deflected about 50 degrees towards it.

Thus it will be seen that any span on which the heavy ice load had not dropped, and which had adjacent unloaded spans, would probably short-circuit a line with vertical spacing of wires as described above.

A number of observations were made on the line when sleet, snow or frost was on the cables, and the unstable conditions of the spans observed were so startling that it was decided to make a series of tests to determine what the principal features were that produced the changes in sag.

It was desired to ascertain:

First. The influence on the loaded span of the elasticity of the cable.

Second. The effect of swing of insulators.

Third. The effect of using strain insulators at frequent intervals.

Fourth. The combined effect of the above conditions.

These tests were made over what was considered at the time a rather large range of equivalent ice loading, but subsequent information shows that weights of ice greater than the maximum used in these tests must be provided for, in designing lines for some localities.

Reference to Fig. 3 will show the experimental line constructed. A level stretch of ground was selected and five spans of line were erected, using six 60 ft. (18.3 m.) cedar poles 750 feet (228 m.) apart in a straight line.

Heavy crossarms were attached at the top and spaced seven feet (2.13 m.) to reproduce the same spacing of arms as on the steel towers. Four units of the disk insulator type were attached to the ends of the arms, these units giving identical suspension with that on the towers. The insulators weighed about 46 lb. (20.9 kg.).

Aluminum cables of 270,000 cir. mils (136.8 sq. mm.) section (the same as on the towers) were then strung on the insulators, the ends being dead-ended at the first and sixth poles. This cable weighed approximately 1315 lb. (595 kg.) per mile (1.61 km.), with an average ultimate strength of 24,000 lb. (10,900 kg.) per square inch (6.45 sq. cm.) and an elastic limit of approximately 14,000 lb. (6350 kg.) per square inch (6.45 sq. cm.);

The cable was strung according to a temperature-tension curve based on a maximum condition of stress of −30 deg. fahr. (−34.4 deg. cent.) with ¼ in. (0.635 cm.) of solid ice around the cable and with a 60-mile (96.5-km.) (actual velocity) wind blowing at right angles to the line. Under this condition the cable would be stressed to the elastic limit as given above.

The crossarms and poles were rigidly guyed, with turnbuckles in the guys to maintain poles and arms in a constant position.

Marker poles were set up at the center of each span to measure the sags and changes in sags. Transits were used to determine any movement of arms or poles.

During the tests described below the temperature ranged between 58 deg. fahr. (14.4 deg. cent.) and 72 deg. fahr. (22.2 deg. cent.), but the influence of this change of temperature

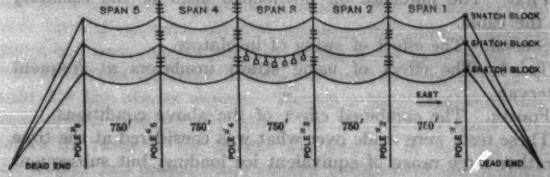


FIG. 3—EXPERIMENTAL LINE CONSTRUCTED NEAR JAMIESON, WASH., TO DETERMINE THE EFFECT OF ICE LOADINGS ON LONG SPANS OF ALUMINUM WIRES, USING SUSPENSION AND STRAIN INSULATORS.

was found to be so small as to be beyond the accuracy of the test. No wind was blowing at the time of taking readings.

To reproduce as nearly as practicable the condition of ice loading on the conductors of the steel tower line, seven concentrated loads were hung from the conductor, equally spaced in the span.

This is not an exact representation of ice load on a cable, yet loads so spaced would give results comparable with those under operating conditions, since it has been observed that ice or sleet forming on wires does not do so with mathematical uniformity.

The vertex of the span is shown plotted in the curves, and is measured on all three cables from the same common point.

It is also to be remembered in this connection, that the three conductors were normally seven feet (2.13 m.) apart in the vertical plane.

First Test. The middle cable in span 3 (see Fig. 3) was loaded with various amounts to represent ice loading. The sags of each span, insulator deflections, and the distance were measured from the nearest pole to the point where the middle cable crossed the cable below.

This is equivalent to having strain insulators every five spans with ice loading on the middle span and with the other spans bare.

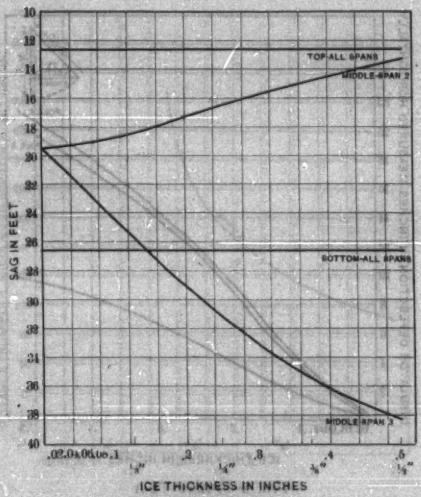


Fig. 4—First Test.
Middle wire in span 3 loaded.

The results are plotted in Figs. 4, 5 and 6.

Second Test. The middle cable in span 1 was loaded, this being a test having the equivalent of a strain insulator at one end of the span.

This test shows the different deflections of insulators and sags, and gives an idea of the decreasing effect in the spans out along the line. Curves in Figs. 7, 8 and 9 apply to this test.

Third Test. All tension on the middle cable in spans 2 and 4

affecting span 3 was taken out, and the insulators on poles 3 and 4 were allowed to swing towards span 3.

This test shows the great increase in sag due to swing of the insulator alone, and a further increase of sag (but of comparatively small amount in proportion) due to the elastic properties of the wire.

Reference to curves in Figs. 10, 11 and 12 will show the results.

Fourth Test. Strain clamps were placed on the ends of the

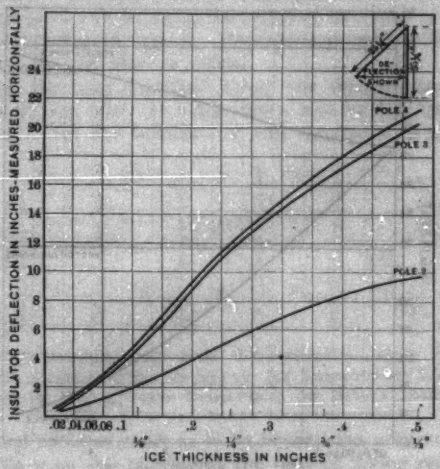


FIG. 5—FIRST TEST

Middle wire in span 3 loaded. Curves show deflections of insulators holding middle wire.

middle cable in span 3, and therefore the various loadings applied showed the effect of the elastic properties of the cable alone.

Fig. 13 covers this test.

The results of the above tests showed that for this particular tower line, its combination length of spans, size and material of wire, and the character of weather conditions, called for a change in arrangement of conductors from the vertical plane. Therefore the point of attachment to the crossarm of the top

insulator was moved in towards the tower, the middle cross-arm lengthened and the attachment to the bottom arm left as originally constructed.

The conductors were then no longer in a vertical plane, and one winter's experience has shown no short circuit, though the horizontal clearance between vertical planes through the cables is not as much as would be provided on a new tower.

The conclusions to be drawn from this experience are more

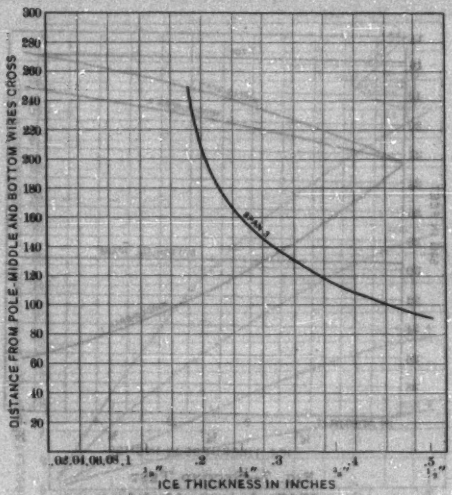


FIG. 6—FIRST TEST

Middle wire in span 3 loaded. Bottom wire unloaded.

than simply the advisability of changing wires arranged in a vertical plane, since it is also a fact that with long spans and wires arranged in a horizontal plane, although the conductors will no longer cause short circuits, they will nevertheless sag down within unsafe distances of the ground.

Therefore, in designing a transmission line with suspension insulators, a more careful examination should be made of *all* the mechanical features of the construction under consideration.

It is obvious that the length of span should be adjusted to

the material and size of the conductor, to the weather conditions experienced or expected, the voltage of the line, and therefore the length of the suspension insulators. The question of right of way also must be considered, and the final test of the allowable amount of expenditure for the service to be performed by the line, will set the limits of construction.

Since a conductor should be strung with due regard to the maximum stress at low temperature, ice and wind loading (as estimated from records in the district where a line is to be

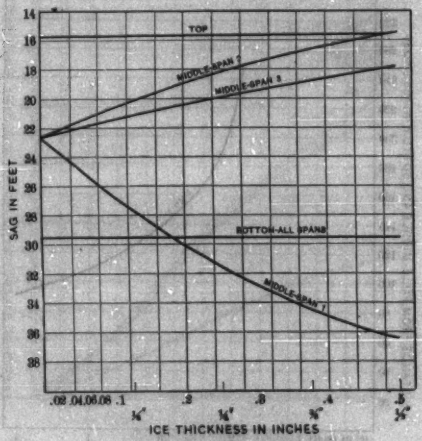


FIG. 7—SECOND TEST
Middle wire in span 1 loaded.

constructed), it is plainly desirable that a conductor having the highest elastic limit should be selected.

If the electrical characteristics of high strength steel cable and its price made it worthy of consideration, it should be obvious that the steel cable could be strung in such a flat catenary that the loading of ice on one span with adjacent spans unloaded, would not cause very much transference of sag to the loaded span.

The use of such cable would of course require strain insulators at suitable points to maintain its position, especially at places

where change of grade occurred. The use of steel-cored aluminum or steel-cored copper, or of bimetallic cable composed of steel wires surrounded by copper, and hard drawn copper of the highest strength, can all be considered with reference to the length of span and sag when using suspension insulators.

The tests described show the great influence of length of insulator on the increased sag, and it appears that notwith-

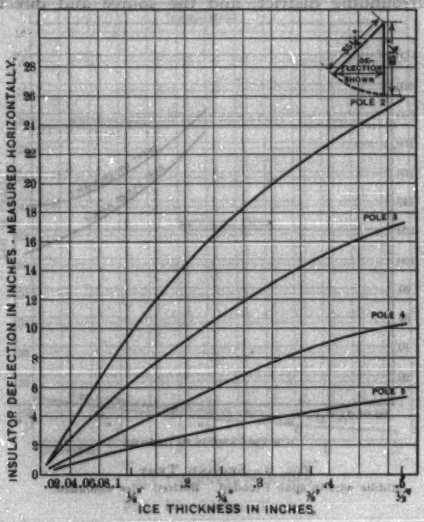


FIG. 8—SECOND TEST

Middle wire in span 1 loaded. Curves show deflections of insulators holding middle wire.

standing the great advance made by insulator designers in bringing out the suspension type, definite endeavor should be made to shorten up the insulators as much as is practical, especially for high-voltage work, where long length of insulators and small light-weight conductors both tend to aggravate the effects shown in this paper.

One of the most difficult features to consider is that of weather

effects, especially the simultaneous conditions of low temperature, ice or sleet and wind. This is especially true in the West, where Government weather stations are not located near each other, and where the district to be traversed by a line is sparsely settled. There is then no fund of information on which to draw, and the general judgment of the engineer must be relied upon. The engineer should inform himself on the method of formation of sleet and frost, and as to the general topography of the surrounding district, and the source and direction of

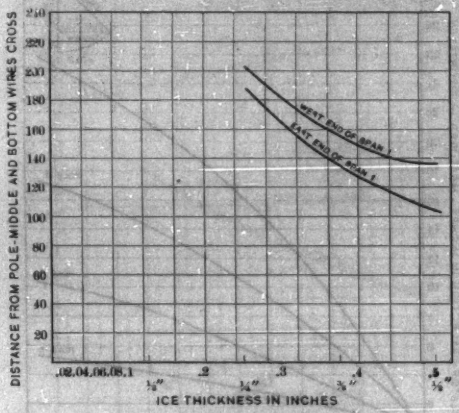


FIG. 9—SECOND TEST
Middle wire in span 1 loaded. Bottom wire unloaded.

travel of the storms which will reach the line. Such general information can usually be secured.

In the case of the tower line described above, it can be stated that the line runs in a northwesterly direction from Spokane, and is at an average altitude of about 2000 feet (610 m.) above sea level.

Two specific kinds of trouble were experienced, one due to very heavy hoar frost being deposited by fogs from the Columbia River valley to the southwest, and which melted rapidly as the fog lifted and the sun came out, this melting usually occurring on the different spans at different rates.

The other weather effect was the deposition of wet snow driven by a hard wind from the southwest, approximately at right angles to the line. This wet snow load sometimes froze solid and was of unusual shape. The outside contour of the snow was approximately that of a flattened ellipse with the conductor at one focus, the snow adhering and piling up on the windward side of the conductor, but not on top. It has

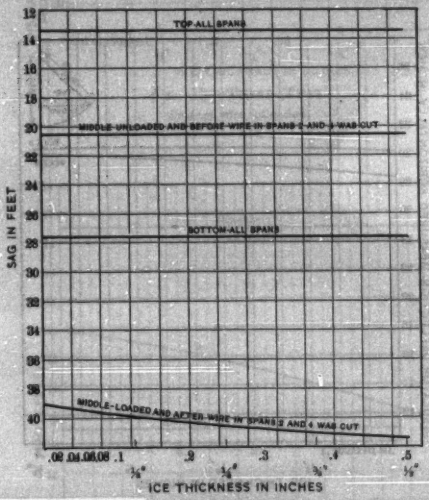


FIG. 10—THIRD TEST

All tension in the middle wire in spans 2 and 4 was taken out and the insulators on the middle wire in span 3 allowed to swing toward span 3. Span 3 was then loaded. This was equivalent to cutting the wires in spans 2 and 4 near the insulators at poles 3 and 4.

also been found that heavy fogs would deposit in the same manner.

Authentic reports on ice loading of telephone and high-tension wires in this district show that the dimensions of such deposits have been about 1½ inches (3.81 cm.) in the vertical plane by 3½ inches (8.9 cm.) in the horizontal, on a No. 9 B.w.g telephone wire, the weight per foot (0.3048 m.) of deposit being 0.8 lb. (0.363 kg.), all by actual measurement.

In another case of a No. 0 aluminum cable, the dimensions of the deposit were $1\frac{3}{4}$ inches (4.45 cm.) thick by 6 inches long (15.2 cm.).

The outside surface of such deposits is very rough and it is useless to use the ordinary formula in calculating wind pressure, as the surface is more nearly that of a plane than a round smooth wire or stranded conductor.

In the cases of wet snow deposits, a high wind usually ac-

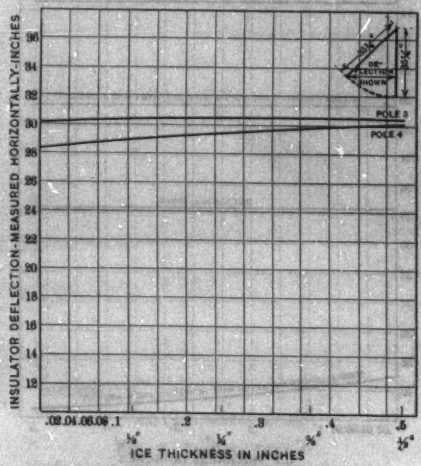


FIG. 11—THIRD TEST

Curves show deflections of insulators holding middle wire in span 3

companied the snow, with the temperature around the freezing point.

Financial considerations will generally limit the reduction of length of span, but a carefully made total cost curve of different tower spacings will frequently show that the cost over a wide range of spacing is very nearly constant. This is especially true if the proper allowances are made on cost of towers, etc., for the different spacings. In such cases, some consideration should be given to the smaller maintenance expense and

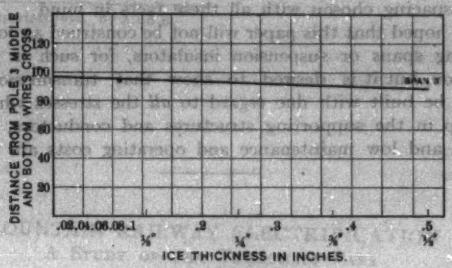


Fig. 12—Third Test

Bottom wire unloaded.

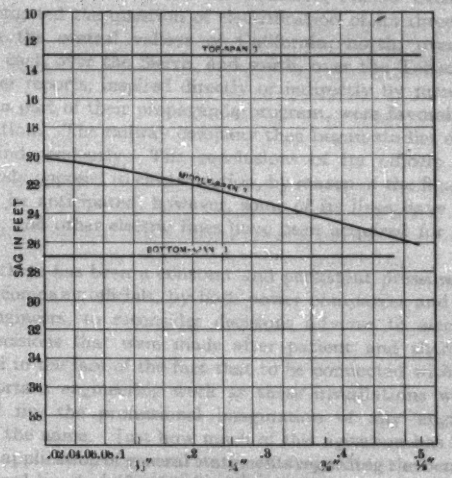


Fig. 13—Fourth Test

Strain clamps were placed on the middle wire in span 3 and the wire fastened solidly to the crossarms. Span 3 was then loaded. This was equivalent to a line with strain insulators at every tower.

more reliable operation of the shorter spans, and the final tower spacing chosen with all these facts in mind.

It is hoped that this paper will not be construed as condemning long spans or suspension insulators, for such is not the intention, but it is desired to show that transmission lines should be built with due regard to *all* the stresses which will develop in the supporting structures and conductors, if good service and low maintenance and operating costs are desired.

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 10, 1913.

Copyright 1913, By A.I.E.E.

MOUNTAIN RAILWAY ELECTRIFICATION

A Study of the Tehachapi Pass

BY ALLEN H. BABCOCK

During the past ten years the Southern Pacific Company has investigated the question of electrification of its three outlets from the central valleys of California, north, over the Siskiyou, east, over the Sierra, and south, over the Tehachapi. The earlier reports, inspired directly or indirectly by manufacturers as a part of their propaganda program, were favorable to electrification. The railway company then began studies of the subject, independently. The conclusions of its officers were unanimously opposed to electrification, by reason of the financial results to be anticipated; however, some of its lines have been electrified, and other electric lines have been acquired for good reasons.

Lately there has been a constant and persistent pressure put upon the company officials, by both power companies and consulting engineers, to reconsider decisions adverse to electrification, decisions that were made after patient and thorough study, and in the face of the fact that to be connected with any such important engineering work as these installations would be, would fire the professional imagination of any engineer worthy of the name. Just how much of this agitation has been due to the application of general statements regarding the benefits to be secured by electrification, to the particular problems presented by west coast mountain railroading, is hardly susceptible of direct determination. It is possible, however, that much of it is due to the effect that such hypothetical studies and papers as have been published recently, have produced upon executives, who, however skilled they may be in their specialties, only in

rare instances are sufficiently experienced technically to be capable of forming independent opinions on engineering matters. It is a fact that reports adverse to electrification in the hands of these same executives, often cause disappointment and sometimes arouse criticism.

Here, then, are two opposing parties; the one with things to sell, (apparatus, power, engineering skill), the other with a service to be maintained, at decreased cost if possible, but maintained at any cost it must be: the first reports favorably upon projects that the second considers unfavorably with equal positiveness. Some things must be unknown to both. Either the radicals have not all the facts upon which to work, or the conservatives cannot interpret their facts correctly.

Words have been multiplied with reference to the subject until aspiring authors well may pause before adding fuel, not to say fat to the fire; but it is with these thoughts in mind this paper is written, not with the intent to offer anything original in the study of such problems but to give the facts of a typical west coast mountain railroad district and their interpretation as seen by one whose reports heretofore have been responsible for many adverse decisions in such matters.

It is not intended to be the final word on the subject of electrification of this district, but it is the result of a study recently made to determine whether there was such a reasonable chance for profitable electrification as would warrant a very considerable expense in time and money, such as was incurred a few years ago in an exhaustive and final study of the Sierra problem, for example.

If through the facts given herein, and in the discussion thereof, a better mutual understanding will be reached, its purposes will have been served.

Physical Characteristics

West Slope, Bakersfield to Summit ..... 49½ miles
- Vertical rise ..... 3764 ft.
- Average grade ..... 1.44 per cent
- Average curvature equal to a constant 3 deg. curve.
- Total curvature, 7944 deg., of which 6969 deg. are between Caliente and Summit (27.2 mi.). The loop curve has a total curvature of 566 deg. 33 min. 12 sec.

East Slope, Mojave to Summit ..... 18.3 miles
- Vertical rise ..... 1285 ft.
- Average grade ..... 1.33 per cent
- Average curvature (as above) ..... 0.79 deg.
- Total curvature ..... 765 deg.

The ruling grade on each slope is 2.2 per cent, but these grades are not compensated for curvature so that in effect the ruling grade is 2.4 per cent. The maximum grades are long enough to fix the weight and power of the locomotives. The average distance between sidings is three miles, approximately.

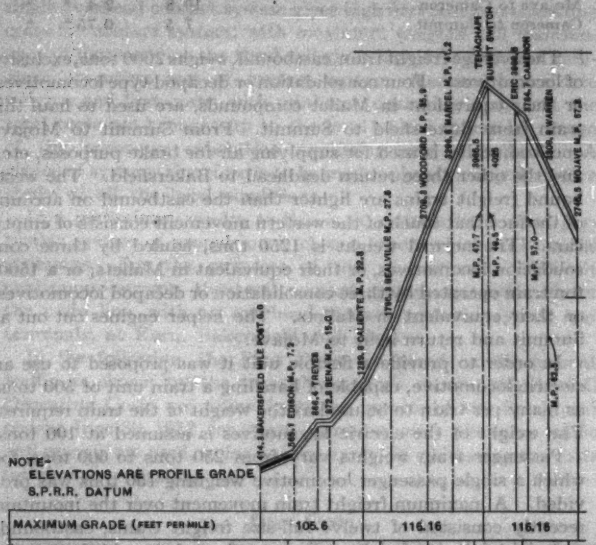


FIG. 1—CONDENSED PROFILE, TEHACHAPI PASS

In determining energy consumption of trains moving over the mountain the actual characteristics of the line were used, (see Appendix K), but in determining load diagrams and substation spacings and capacity, the following close approximations were

made to take care of the ruling grade, curves, etc. (For their application see Appendix A.)

Section	Miles	Average grade
Bakersfield to Edison	7.2	0.5 per cent
Edison to Caliente	15.1	1.5 " "
Caliente to Summit	27.2	2.4 " "
Mojave to Cameron	10.8	2.4 " "
Cameron to Summit	7.5	0.75 " "

The average freight train, eastbound, weighs 2000 tons, exclusive of locomotives. Four consolidation or decapod type locomotives, or their equivalent in Mallet compounds, are used to haul this train from Bakersfield to Summit. From Summit to Mojave one locomotive is used for supplying air for brake purposes, etc., and the other three return deadhead to Bakersfield. The westbound freight trains are lighter than the eastbound on account of the fact that much of the western movement consists of empty cars. The normal weight is 1250 tons, hauled by three consolidation locomotives, or their equivalent in Mallets; or a 1500-ton train operated by three consolidation or decapod locomotives, or their equivalent in Mallets. The helper engines cut out at Summit and return light to Mojave.

In order to provide a flexible unit it was proposed to use an electric locomotive, capable of handling a train unit of 500 tons, as many per train to be used as the weight of the train requires. The weight of the electric locomotives is assumed at 100 tons.

Passenger train weights vary from 250 tons to 600 tons, for which a single passenger locomotive weighing 150 tons was provided. A maximum freight train movement over the mountain recently consisted of twelve full-size freight trains, eastbound, and eight full-size freight trains, westbound, in addition to the normal passenger movement, which is seven regular trains each way per day, with occasional extras and second sections.

The track, particularly on the west slope, is laid for the greater part of the distance in rough country, in fact between mile posts 326 and 361 all the track, with the exception of a short stretch near Caliente, is in cuts or on fills. It may be said generally that at least half the track is laid in conditions where any overhead contact system would require, necessarily, very expensive steel pole or bridge construction. In addition to the above, there are 18 tunnels, in none of which the vertical clearance is more than 18½ ft., and 60 per cent of their total length is on 10-deg. curves. A detailed list of tunnels is given in Appendix L-1.

Experience with similar earlier reports has shown that, in general, there is little difference in total first cost and annual operating costs, whether an overhead system or the third rail system be considered. A double overhead contact system gives maximum first cost and operating costs for contact system, and minimum weights, costs and maintenance of locomotives; a single overhead contact system gives high first cost and operating costs for contact system, with maximum weights and maintenance of locomotives; the third rail gives high first cost and minimum operating cost of contact system, medium locomotive weights and first costs, with minimum operating costs, but the total costs are brought up to the level of the others by reason of the necessary substation apparatus and attendance. A choice of systems therefore is to be made only after an exhaustive study of all the local conditions.

In a preliminary study, as this is, it matters little what particular system of propulsion is chosen, upon which to base the estimates. For the purposes of this discussion a 2400-volt continuous-current, third-rail contact system was selected for the main line, with an overhead contact system in yards and terminals, at Kern, Bakersfield and Mojave.

In the following, the First Costs are based on the present traffic as shown by the train dispatcher's sheets; the Annual Operating Costs are taken from the reports of the fiscal year ending June 30, 1912, for steam operation, while the same traffic and reports are used, as far as they apply, in estimating the costs for electric operation.

First Costs

Substations,	Appendix A	$1,610,000
Generating station,	" B	1,760,000
Transmission system,	" C	430,050
Contact system (yards)	" C	155,250
" " (line),	" A	825,000
Bonding,	" A	122,300
Block signals,	" D	175,000
Shops and inspection shed,	" E	10,000
Electric locomotives,	" F	2,085,000
Total		$7,172,600
Credit by steam locomotives released for service on other divisions,	Appendix G	1,464,900
Net first cost		$5,707,700

ANNUAL OPERATING COSTS
(Steam-generated power)

		Steam	Electric
Substation labor and supplies,	Appendix A.....		$59,700
Power house labor and supplies	" B.....		84,780
Transmission and contact system maintenance,	" C.....		36,576
Maintenance of way as affected by locomotives,	" H.....	$126,890	83,285
Locomotive repairs,	" I.....	270,990	70,701
Loco. enginemen, (passenger),	" J.....	48,300	29,100
Fuel,	" K.....	240,852	100,530
		$687,032	$464,672
Bond interest at 4½ per cent on net first cost.....			256,847
Totals.....		$687,032	$721,519

Net loss, $34,487

In the above no account is taken of items not affected by character of motive power: freight enginemen, and all train crew wages, repairs to cars and maintenance of way as affected by cars—for example.

The net loss under proposed electric operation is so small that it might be wiped out by a reasonably small change in the assumptions; in fact, at this stage of similar investigations often there is a temptation to search for opportunities to change this, or to modify that, as the necessities of the case demand. This important fact should be borne in mind, however, that in the foregoing no account is taken of taxes and depreciation, both of which must be paid, some time, by some one, to the extent of at least 5 per cent of the net investment, which increases the net loss by approximately $285,000 per year.

It may be asked, why is depreciation not taken into account in the usual manner? The answer is, since there is a loss, or at least no profit shown, and since to add depreciation would be to make a bad matter only worse, nothing is to be gained by entering into the academic discussions that inevitably follow the opening of a subject concerning which opinions reasonably may differ as widely as on this much disputed particular.

But power may be purchased, as is often suggested by those with power for sale, hence it is proper to determine at what rate this power may be purchased and come out even as compared with operation by steam-generated power. Obviously any rate less than this will be profitable.

With purchased power, the total investment will be diminished

by the costs of 20 miles of transmission line and of the generating station, it being assumed that power will be delivered at some one point on the right-of-way, whereas local conditions located the steam station 20 miles off the right-of-way (see Appendix B).

The net first cost was		$5,707,700
Transmission line, Appendix C	$120,000	
Generating station " B	1,760,000	1,880,000
Leaving a net investment with power purchased		$3,827,700

ANNUAL OPERATING COSTS
(Power purchased)

		Steam	Electric
Substation labor and supplies,	Appendix A		$59,700
Transmission and contact systems maintenance,	" C		35,576
Maintenance of way as affected by locomotives,	" H	$126,890	83,285
Locomotive repairs,	" I	270,990	70,701
Loco. enginemen, (passenger),	" J	48,300	29,100
Fuel,	" K	240,852	
		$687,032	$278,362
Bond interest at 4½ per cent on net first cost			172,247
Totals		$687,032	$450,609

The difference, $236,423, should be decreased by $191,385, (the approximate tax and depreciation rate of 5 per cent on the net investment of $3,827,700), and there is left the wholly inadequate sum of $45,038 with which to purchase 53,000,000 kw-hr. at a load factor of about 20 per cent; with no profit to show for an investment of nearly $4,000,000.

For the sake of the argument let the depreciation be neglected and let it be considered that $236,423 are available for the purchase of power under the operating conditions of the service. At any time there may be four passenger and four freight trains pulling up hill simultaneously, taking a total of 32,720 kw. alternating-current input to the line. This is not the maximum number of trains that is on the mountain regularly, but represents only those taking power. A slight derangement of schedules, or an extra freight movement, citrus fruits or oil, or a blockade, for example, will cause congestion beyond any possibility of estimating. This traffic must be handled as circumstances require. It cannot be spaced conveniently for power demands, as many engineers and power men have suggested, but the term-

inal yards must be cleared as the cars accumulate. Is there any power company in the west coast country, or even beyond the reach of such a natural power source as Niagara, that would care to undertake such a load for any such yearly return as that named in this paragraph? It would net about 4½ mills; a rate that neither the purchaser nor the seller could afford to consider.

In the face of the foregoing it is difficult to see how any recommendation in favor of electrification can be made, if the opinion is based on the direct financial profit to be realized; in other words, this case is merely another example of the fact often noted, that in the great majority of cases the profits from electrification must be realized indirectly rather than directly,—increased track capacity, postponing second- or double-tracking, or the like.

It may be urged that a larger district would make a better showing. In this connection it may be noted that the line from Bakersfield to Summit is almost identical with half of the line assumed in Mr. Hobart's paper on 2400-*Volt Railway Electrification*.* On each side of the summit Mr. Hobart's assumed line is 3800 ft. rise in 48 miles with the ruling grade of 2.2 per cent, while the west slope of the Tehachapi is 49½ miles, rise of 3764 ft. and a ruling grade of 2.4 per cent. Also Mr. Hobart assumes freight train weight on heavy days of 1800 tons as against 2000 tons on the Tehachapi. Furthermore, the Sierra study covered a district more than double the length of the Tehachapi, and the result was the same.

In the various appendices will be found complete details of all the elements of the investigation, as noted by the cross references given after the various items of the tabulations herein.

Acknowledgments are hereby made to Mr. G. W. Welsh and Mr. F. E. Geibel, both assistant engineers in the electrical engineer's office, Southern Pacific Company, for assistance in the preparation of this paper. The former made a thoroughly painstaking study of the problem as a whole, and to the latter is due the novel method of determination of substation spacing and capacity as detailed in Appendix A.

APPENDIX A

Substations

Substation Spacing and Heating Loads. It is not the purpose here to go into a theoretical discussion of the economical spacing

*See p. 1149, this volume.

of substations, balancing off the losses and fixed charges of the distributing system against the losses and fixed and operating charges of the substations. Any such discussion requires the lengthy consideration of various operating conditions which seldom, if ever, are obtained in practise; hence the determination leads nowhere.

The following is simply a brief description of a very convenient and quick method of determining the feeder and substation layout in preliminary studies of the electrification of mountain divisions of steam railroads. The method was developed by Mr. F. E. Geibel, assistant engineer, Southern Pacific Company, in the original study of the problem.

The conditions, as set forth in the general study, require an average train speed over the electrified section. It is therefore necessary to maintain an average voltage over the sections between substations. Formulas for the average volts drop over the section were deduced as follows:

Let L = distance in miles between substations.
I = current per train in amperes.
R = resistance of distributing system in ohms per mile of circuit.
A = distance in miles between first and second trains.
B = distance in miles between second and third trains.
V = volts at substation.
E = instantaneous volt drop on line.
D = average volts drop over section between substations.
X = distance in miles between first train and a substation.

Considering first only one train between substations:

$\left(\frac{L-X}{L}\right) I$ = current drawn from one substation.

XR = total resistance to same substation.

Therefore $E = \frac{RI}{L}(XL - X^2)$

$$\text{but } D = \frac{\sum_0^L E}{L} = \frac{RI}{L^2}\int_0^L (XL - X^2)\,dX$$

$$= \frac{1}{6} R I L = \text{average volts drop.}$$

Similarly, formulas for two and three trains in a section were deduced, for average drop as follows:

One train between substations, $D = \frac{1}{6} R I L$

Two trains " " $D = \frac{1}{6} R I \left(2L - \frac{3A^2}{L} \right)$

Three " " " $D = \frac{1}{6} R I \left[3L - \frac{2(2A+B)^2}{L} \right]$

If the trains are following at equal distances then $A = B$ and the last formula becomes

$$D = \frac{1}{6} R I \left[3L - \frac{2(3A)^2}{L} \right]$$

The loads on the substations were plotted graphically for several substation spacings up to twenty-five miles, and the heating loads were computed for each spacing. It was found, however, that the heating load varied approximately as follows:

Total heating $= 2 \left(\frac{L}{A+B} \right) VI$ for trains alternately A and B miles apart, when the distance between substations is equal to or greater than the greater spacing between the trains. For trains of equal distance apart, total heating $= 2 \left(\frac{L}{2A} \right) VI$. VI is the amperes per train multiplied by the substation voltage.

It is to be noted here that all of the above expressions apply only to direct-current systems and cannot be used on single-phase systems without complication. It is, also, to be noted that the formulas are deduced assuming trains running in one direction only, as, on the grades considered, the trains coming down grade do not draw a running current but only a small current for control purposes.

In applying the formulas to the problem in hand the following assumptions were made:

2000-ton trains with four 100-ton locomotives per train.

Trains 15 miles per hour, spaced alternately 5 and 10 miles apart.

Locomotive efficiency 90 per cent. Train resistance 6 lb. per ton.

Substation voltage 2400. Train voltage 2100 average.

In Fig. 2 will be found curves showing the total conductivity, in terms of total million circular mils of copper equally divided between positive and negative circuits, required to give the average voltage over the section for various grades. These curves were plotted from the formulas given above. With substation spacings up to 8.65 miles, the average drop is greater with one

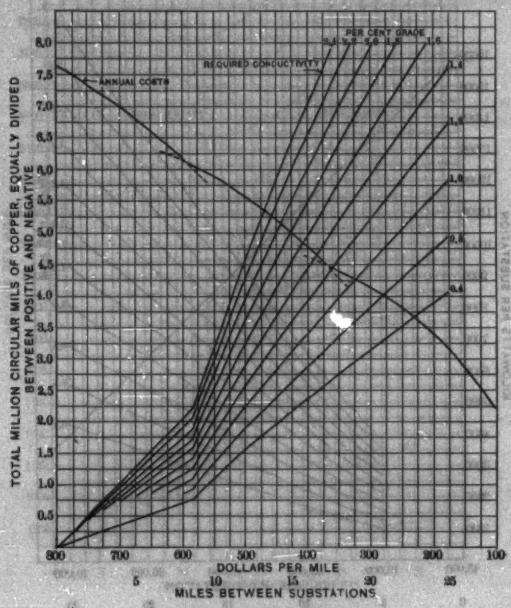


FIG. 2—CONTACT SYSTEM

train in the section, and between 8.65 miles and 26.9 miles the average drop is greater with two trains in the section. Hence the break in the curves at 8.65 miles.

There is also plotted in Fig. 2 a curve giving the annual costs per mile on a contact system of the required conductivity. A contact rail system was considered with no positive feeders but 75-lb. old rail as negative feeder. The annual cost curve

shows three distinct sections, namely: the lower section, no negative feeder; the middle section, one 75-lb. rail negative feeder; and the upper section, two 75-lb. rail negative feeders. As worked out, however, the system required no negative feeder. From Fig. 2, it is seen that the annual cost per mile on the con-

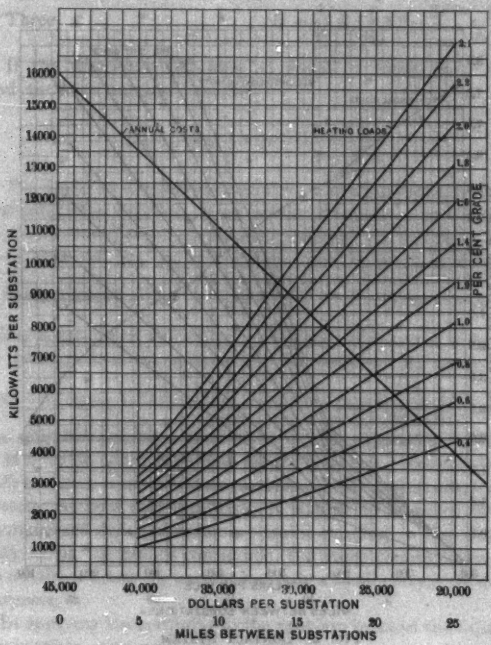


FIG. 3—SUBSTATIONS

tact system for any given substation spacing and grade can be read directly.

Similarly from Fig. 3 the heating loads on substations for any given spacing and grade may be read off, or, if referred to the annual cost curve, the annual cost per substation is given. This

latter value divided by the spacing gives the substation annual costs per mile.

The above annual costs were taken at various substation spacings on several given grades and the results, the total annual costs per mile, were plotted in Fig. 4. This gives a series of

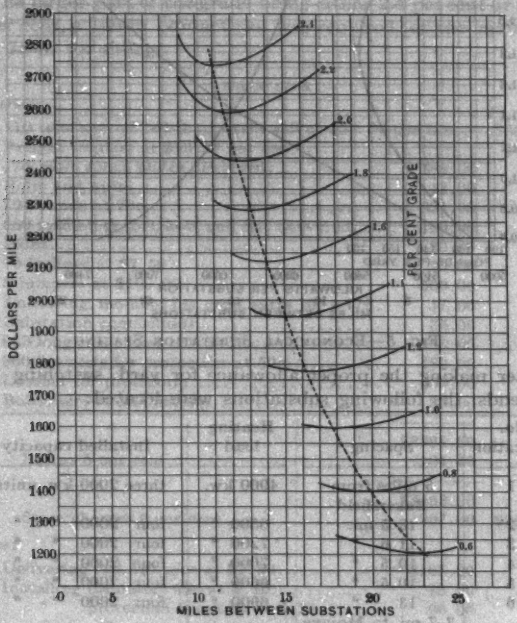


FIG. 4—TOTAL ANNUAL COSTS

curves, the minimum of each being the economical substation spacing on the given grade. These results were transferred to Fig. 5 which shows, for any given grade, the economical spacing, the heating load on substation and the size of contact rail required.

As stated in the report, the track district under study was divided into several sections of average grades. By applying

the latter curve, therefore, to these sections the spacing and heating loads of the substations are easily determined.

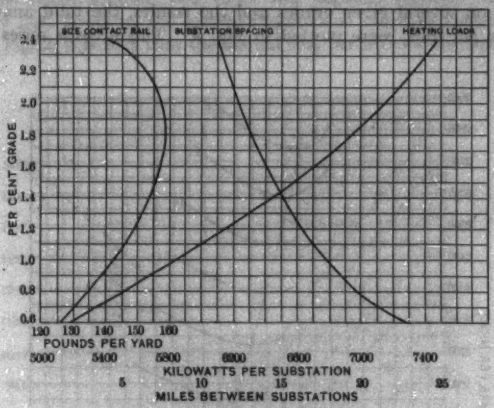


FIG. 5—ECONOMICAL SUBSTATION SPACING

After making the proper allowance for yard switching and stub ends, the following substations were located:

No. substation	Spacing	Heating load	Installed capacity
1	5 miles from Bakersfield	4900 kw.	three 2000-kw. units
2	13.5 mi.	6500 "	four 2000 " "
3	11.6 "	7200 "	four 2000 " "
4	10.5 "	7000 "	four 2000 " "
5	10.5 "	6600 "	four 2000 " "
6	13 "	6900 "	four 2000 " "
	3.7 mi. to Mojave		

SUBSTATIONS

The unit first costs used are as follows:

$35 per installed kw.

The above is based on a recent west coast installation, corrected for 2400-volt apparatus.

OPERATING COSTS

1 *Station*—6000 kw. capacity. Labor, 3 shifts,

2 men each, $1300 and $1000..... $6900

Repairs and supplies..... 2200 $9100 $9,100

5 *Stations*—8000 kw. capacity. Labor, 3 shifts, 2 men each, $1300 and $1000	$6900		
Repairs and Supplies	2500		
		$9400	$47,000
2 Substation foremen at $1800			3,600
			$59,700

Contact Rail, 2400 Volts

The larger part of the grade being either 2.4 per cent or under 1 per cent, a 140-lb. contact rail was required for the main line and 75-lb. for sidings.

MAIN LINE

Material:		
110 tons special 140-lb. contact rail at $33.00 per ton		$3630.00
Freight thereon at $13.50 per ton		1485.00
176 pairs splice plates delivered	$88.00	
Bolts and nuts	12.00	
704 bonds at 74c	521.00	
480 insulators, brackets and felt delivered	480.00	
Paint	20.00	
10 inclines at $7.50	75.00	
5 jumpers at $100.00	500.00	
Anchoring, modified ins. caps, extra 10c x 176	17.60	
Substation connections	35.00	
960 long ties excess cost at 50c	480.00	
960 brackets for protection at 50c	480.00	
Lumber for protection	500.00	
Bolts, screws and fittings	80.00	
	$3288.60	
Extras 5 per cent	164.40	
	$3453.00	
Store charges 6 per cent	207.00	$3660.00
Labor:		
Delivering rail 110 tons at $1.50	$165.00	
Installing insulators 480 at $.10	48.00	
" protection brackets at $.10	96.00	
" rail	200.00	
" bonds at $.30 ea	211.20	
" protection	400.00	
Painting	100.00	
Work train	100.00	
	$1320.20	
Extras 10 per cent	132.00	$1452.20
		$10,227.20

Say $10,225.00 per mile

Material:	SIDINGS	
59 tons special 75-lb. contact rail at $46.50 del.		$2740.00
352 bonds at 60c	$211.20	
Other material	2560.80	
	$2772.00	
Extras 5 per cent	138.60	
	$2910.60	
Store charges 6 per cent	174.60	$3085.20
Labor:		
Delivery of rail 59 tons at $1.50	$93.50	
Installing bonds at 30c	105.60	
" insulators	48.00	
" protection brackets	96.00	
" rail	100.00	
" protection	400.00	
Painting	100.00	
Work train	100.00	
	$1043.10	
Extras 10 per cent	104.30	$1147.40
		$6972.60
Say		$7000.00

The above is based on Pennsylvania R.R. type of third rail with protection installed on both sides. Cost of rail is based on New York Central cost of special rail plus freight charges. Cost of specialties is taken from quotations. Labor is according to west coast practise.

MAIN LINE BONDING

Two 10-in., 450,000-cir. mil bonds per joint.		
Bonds	$570.00	
Cross bonds	75.00	
Labor	375.00	
	$1020.00	
Extras	102.00	$1122.00

SIDINGS AND YARD TRACK BONDING

Two 4/0 bonds per joint.		
Bonds	$320.00	
Cross bonds	100.00	
Labor	400.00	
	$820.00	
Extras 10 per cent	80.00	$900.00

The above is based on the actual cost of bonding in an installation recently made in the vicinity of San Francisco. The fact that the track would be bonded under heavy traffic should not be overlooked.

TOTAL FIRST COSTS

Substation and Distribution

Substation		
46,000 kw. at $35		$1,610,000
Contact rail		
65.84 mi. main line at $10,225	$673,000	
21.60 mi. sidings at $7000	152,000	
		825,000
Bonding		
65.84 mi. main line at $1120	$73,800	
21.60 mi. sidings at $900	19,440	
32.29 mi. yard tracks at $900	29,060	122,300
		$2,557,300

Annual Costs

For the reason that one organization should maintain all transmission and distribution system, the annual costs of maintenance and repair for contact system are to be found under Transmission Line Costs, Appendix C.

APPENDIX B

Generating Station

Two principal considerations fixed the generating station at a distance from the track: fuel and water.

Twenty miles off the right-of-way from a point 6 miles east of Bakersfield is located a large oil field from which the company obtains much of the fuel oil used in its locomotives. Plenty of water for condensing purposes is obtainable near by. The annual charges on a transmission line under these conditions do not impose so heavy a burden on the operating costs as would the delivery of oil at the right-of-way; besides, to develop sufficient water along the track would cost a great deal. For these reasons the generating station was located in the oil fields on fairly level land where excavating costs were reasonable and on soil sufficiently firm for ordinary foundations.

The load curve, Fig. 6, indicates that a three-unit station is desirable, two units of which would carry the load ordinarily, with one as a spare. A study of the load curve and train diagram fixed the maximum capacity of the units at 18,000 kw. at the two-hour overload rating—an economical size in first cost and in annual operating costs. The point of maximum economy without auxiliary nozzles is in the neighborhood of 10,000 kw., and the hand-operated nozzle will enable the machine to carry

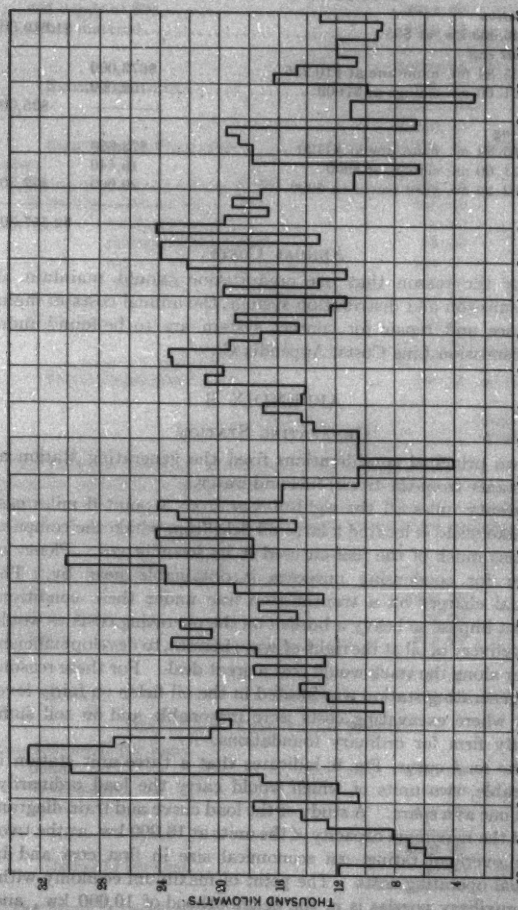


FIG. 6—LOAD DIAGRAM

between 13,000 and 14,000 kw. at the same water rate, with a by-pass for the higher overloads.

The segregated estimated prices are as follows:

Three turbines, 18,000 kw. maximum, for two hours	$400,000
Exciters and battery	25,000
Three condensers and drives	65,000
15,000 h.p. boilers, superheaters, stacks, breeching, brickwork, etc	330,000
Pipe, valves, fittings, covering	75,000
Oil fuel sets, fire, oil unloading, house and boiler feed pumps, heaters	30,000
40,000 bbl. oil storage, blow-off, hot well, house tank, etc	16,000
Crane	12,500
Switchboard and wiring	150,000
Step-up transformers	100,000
Condenser tunnel system	75,000
Superintendence, engineering, drawings, general labor, traveling expense, telegraph and telephone, testing plant, tools, insurance	75,000
Buildings, foundations and excavation	350,000
Incidentals	56,500
	$1,760,000

The very high temperatures in the summer months at the power house location, (which means hot circulating water), require very large condensers.

The station operating force as taken from the average practise in this part of the country is as follows:—

POWER STATION OPERATING COSTS

Labor:			
Superintendent of power			$4,000
Steam:			
1 Chief engineer at	$225	per mo.	2,700
3 Watch engineers at	125	" "	4,500
3 Turbine operators at	95	" "	3,420
6 Water tenders at	95	" "	6,840
6 Firemen at	95	" "	6,840
6 Oilers at	85	" "	6,120
3 Wipers at	75	" "	2,700
1 Boiler repairer	120	" "	1,440
1 Boiler cleaner at	85	" "	1,020
1 Machinist at	110	" "	1,320
1 Machinist helper at	90	" "	1,080
1 Clerk at	90	" "	1,080

Electric:

3 Load dispatchers at	125 " "	4,500
1 Chief operator at	150 " "	1,800
3 Switchboard operators at	110 " "	3,960
3 Asst. " "	90 " "	3,240
3 Dynamo tenders at	80 " "	2,880
3 Dynamo cleaners at	75 " "	2,700
2 Meter testers at	110 " "	2,640
Total power station, labor		$64,780
Repairs, supplies, etc.		20,000
Total per year		$84,780

APPENDIX C

Transmission Line

For the distribution of power along the right-of-way to the different substations there will be required 50.5 miles of No. O twin circuit line, with an addition of 20 miles of the same line from the right-of-way to the generating station, making a total of 70.5 miles of transmission line required. The detail costs following are taken from the actual book costs of a similar transmission line installed recently under practically identical conditions.

Twin Circuit Transmission Line Costs—60,000 Volts
(Assume 3 special and 7 standard towers per mile with suspension insulators, 1 ground wire.)

Material:

3 special towers 3650 lb. each at 5½c delv'd.	$600.00	
7 standard " 3200 " " " 4½ "	938.00	
	$1538.00	
Store charges, one per cent	15.38	$1553.38
126 disk-type insulators at $2.20	$277.20	
108 strain " " " 1.95	210.60	
42 sets hdw. for suspension insulators at $1.20	50.40	
36 sets hdw. for suspension insulators at 1.40	50.40	
1 mi. 7/16 in. high strength ground wire, 19001b. at $3.25 cwt.	61.75	
6 mi. No. 0 copper, 10,122 lb. at 22½c	2277.45	
	$2927.80	
Store charges 6 per cent	175.67	$3103.47
		$4656.85
5 per cent for extras, etc.		232.85
		$4889.70

Labor:			
Blasting and foundations for towers—average	$60.00		
Distribution of steel	2.50		
Assembling	20.00		
Attaching insulators	3.00		
Erecting towers	10.00		
Ten towers per mile	$95.50	$955	
Distributing six cond. and one ground wire		9	
Stringing six cond. and one ground wire		125	
		$1089	
10 per cent for extras and changes		109	$1198.00
			$6087.70

OVERHEAD CONSTRUCTION

Bakersfield and Mojave Terminals and Kern Yards.

Material:		
420 40-ft. tubular steel poles at $65		$27,300.00
50 34-ft. tubular steel poles at $40		2,000.00
380 35-ft. wood poles at $7		2,660.00
85 single brackets for wood poles at $4	$340.00	
40 double brackets for wood poles at $7	280.00	
2260 porcelain strain insulators at 26c	587.50	
1235 wood strain insulators at 60c	741.00	
73,500 ft. 7/16 in. high strength steel strand at $2.60 per C	1,911.00	
5500 ft. 5/16-in. iron strand at $1.25 per C.	68.75	
205,400 ft. 4/0 trolley wire at $130.00 per M.	26,710.00	
1800 trolley clamps at 75c	1,350.00	
100 center trolley supports at 80c	80.00	
1800 suspension insulators at 70c	1,260.00	
	$33,328.25	
Store charges 5 per cent	1,666.50	34,994.75
		$66,954.75
Extra material 5 per cent approx		3,225.25
		$70,180.00
8 anchor bridges (erected)		24,000.00
19,100 ft., 1,500,000-cir. mil copper feeder (erected)		21,729.50
		$115,909.50

Labor:

Erection 420 40-ft. steel poles at $35	$14,700.00	
" 50 34-ft. steel poles at $25	1,250.00	
" 380 35-ft. wood poles at $8.50	3,230.00	
" 425 cross spans at $7.50, $15, and $20	7,600.00	
" trolley	8,240.00	
	$35,020.00	
2 per cent use of tools	700.30	
	$35,720.30	
10 per cent contingencies	3,573.20	39,293.50
Total		$155,203.00
Called		$155,250.00

The foregoing costs are taken, (except as to insulators), from the book costs of a recent installation.

The method of construction is to span as many tracks as are necessary, without throwing track, to use steel poles at the ends of the span wires and to carry the trolley wires from a secondary span wire without the use of catenary construction.

Annual Costs

The total annual costs for maintenance of transmission and contact systems, based on the costs of similar work in other places, are as follows:—

Overhead and Contact Rail

Supt. of power distribution at $175 per mo.	
Clerk at $75 per month	$3,000.00
50.5 miles high-tension transmission at $50	2,525.00
32.5 miles overhead construction at $250	8,125.00
65.84 miles main line contact-rail at $150	9,876.00
21.60 miles sidings contact-rail at $100	2,160.00
67.34 miles main line bonding at 10 per cent	7,548.00
48.99 miles sidings bonding at 5 per cent	2,342.00
	$35,576.00
20 miles additional transmission at $50	1,000.00
	$36,576.00

In the foregoing, the estimate for bonding is based on the life of the rail in the track under consideration, it being considered that when the rail is replaced the bonds will come out and will have only a scrap value, being replaced then by new bonds.

APPENDIX D

Block Signals

At the present time the entire district between Mojave and Bakersfield is protected with automatic block signals of the usual continuous-current track circuit battery type. In case of electrification a great part of this apparatus will have to be replaced with alternating-current track circuit apparatus, because the use of track circuits with propulsion current in the rails requires selective apparatus to prevent false indications. The estimate of the signal department for making these changes is $175,000.

APPENDIX E

Electric Shops and Inspection Shed

For the reason that the company has important division shops located already at Bakersfield, a large item for repair shops is not necessary, it being understood that the heavy electric locomotive repairs would be done in the steam locomotive repair shops. An inspection shed with pits, however, is necessary, for which the lump item of $10,000 was included, this being in the ratio of cost of the track facilities required here to the cost of similar track facilities in a shop recently erected by this company.

Note. The maintenance cost of inspection shed and tools therein is carried under the heading of "Locomotive Repairs"—(see Appendix I).

APPENDIX F

Electric Locomotives

An analysis of the train sheets covering the period of maximum tonnage over the mountain shows that there will be required 47 freight locomotives, and 11 passenger locomotives, which includes a reasonably large allowance, namely, 8 freight and 3 passenger locomotives, for repair and shopping purposes. The locomotives required for this service are so closely similar in characteristics to those upon which quotations were asked recently from the electrical manufacturers that new quotations were not requested for the purposes of this estimate, particularly since the locomotives actually quoted on were for the same operating voltages, etc., as are contemplated herein.

The unit costs were: passenger locomotives $40,000, and freight locomotives $35,000, making a total of $2,085,000 for 47 freight and 11 passenger locomotives.

APPENDIX G

Steam Locomotive Credits

It seems pertinent here to note the very significant fact that while steam locomotives are strictly interchangeable and can be moved from division to division as the necessity for varying motive power capacity develops, by reason of crop movements, or otherwise, the electric locomotives are limited in their field of operation strictly to electrified track, and as far as interchange between divisions is concerned they might as well be of some gage other than standard. An inspection of the records of the operating department shows that during a period of heavy traffic over the mountain there were in actual service 13 passenger, 47 consolidated or decapod and 13 Mallet locomotives, which, if taken at the same valuation as was used in a recent report on the Sierra-Nevada electrification, would represent an investment of $1,220,750, to which should be added at least 20 per cent for extras, shopping, repairs, etc., making the total investment in steam locomotives properly chargeable to this district = $1,464,900. It may be thought that the allowance of 20 per cent for shopping, etc., is not large enough; that the records of the steam motive power department will show a greater percentage of locomotives assigned to a given district and actually out of service; but it should be remembered that in case of sudden demands, steam locomotives are moved from division to division as stated above, and therefore it is not reasonable to charge to this district the total amount of steam motive power that would be required if the district is considered as an isolated entity in operation, as would be the case under electric operation.

APPENDIX H

Maintenance of Way as Affected by Locomotives

Many years' experience in the analysis of track maintenance accounts has shown that, independent of all other considerations, track maintenance as affected by rolling stock can be divided into two heads, locomotives and cars, the segregated costs of which have been determined very accurately. Reduced to dollars and cents, the auditor's accounts show that locomotives of approximately the same weight and run at the same speeds as those contemplated in this report, caused maintenance of way expense at a certain rate per locomotive mile, from which has been deduced the item, $83,285, given in the statement of Annual Operating

Costs. That for steam operation, $126,890, is taken from the records.

APPENDIX I

Locomotive Repairs

The figure given under this item for steam operation is taken directly from the records. The estimated cost of electric locomotive repairs, 4 cents per locomotive mile, is based on our analysis of the best data available for such costs. As to this value, opinions reasonably may differ, but it probably will be recognized that the figure named gives a rather favorable consideration to the use of electric locomotives, since the repair accounts of some of the larger railroads operating the largest electric locomotives in this country show repair costs materially more than 4 cents, all things considered.

APPENDIX J

Enginemen's Wages

In the report it was mentioned that certain items, such as freight enginemen's wages, would not be changed materially by a change in the nature of the motive power. The reason is that the present tendency is toward the operation of large Mallet locomotives, at an advanced rate per 100 miles paid their enginemen. Since the capacity of an electric locomotive unit is essentially the same as the largest Mallet it is felt that the wages paid will have to be the same as for present freight service. The passenger enginemen's wages under electric operation are based on the same wages per locomotive mile as under steam operation, but since the electrics would make unnecessary the use of helpers on the mountain, the total has been reduced by the amount now paid helper enginemen.

APPENDIX K

Fuel

The item $240,852 for fuel under steam operation is taken from the records. It represents the oil issued to the steam locomotives and charged to them at the division cost of oil, which in turn is the cost at the wells, plus transportation charges to the particular division, with a percentage added for store expense and handling.

On the other hand, the item $100,530 for fuel under electric operation, represents the number of barrels of oil estimated to

be consumed in the generating station, at the cost per barrel of oil at the wells plus a small handling charge.

The reasons for locating the generating station at the wells are given in detail in Appendix B. The net result is that the oil costs materially less in the steam generating station than when delivered to the locomotives of the San Joaquin division.

The basis upon which the oil consumption is calculated is as follows:

PHYSICAL CHARACTERISTICS OF TRACK

	West slope	East slope
Distance (feet)	261,300	96,624
Total ascent—east	3,687	5
" " —west	77	1,280
" " —east and west	3,764	1,285
Total curvature	7,944 deg.	765 deg.
Ave. grade per cent	1.44	1.33
" curvature	3 deg.	0.79 deg.

TRAIN RESISTANCE, POUNDS PER TON

	West slope	East slope
Grade	28.8	26.6
Curvature	2.7	0.7
Friction	6.0	6.0
Total	37.5	33.3

Energy, foot-tons per ton of train lifted to Summit:

$$\text{West slope } \frac{37.5 \times 261{,}300}{2000} = 4900 \text{ ft-tons}$$

$$\text{East slope } \frac{33.3 \times 96{,}624}{2000} = 1607 \text{ ft-tons}$$

TONNAGE CONSIDERED

Passenger:

One	250-ton train each way plus 150-ton locomotive	400 tons
One	350 " " " " " 150 " "	500 "
Three	400 " " " " " 150 " "	1650 "
Two	600 " " " " " 150 " "	1500 "
	Total per day each way	4050 "

Freight:	Eastbound	Westbound
Gross tons per year (trailing)	4,798,056	3,167,301
Number of 500-ton units	9,598	6,335
Number of locomotives (minimum)	9,598	6,335
Add 10 per cent for underloaded locomotives	960	633
Total locomotives	10,558	6,968

Summary:		
Gross tons per year trailing	4,798,056	3,167,301
Locomotives at 100 tons	1,055,800	696,800
Total tons per year	5,853,856	3,864,101
" " " day	16,040	10,600

FUEL CONSUMPTION

Passenger: 4050 tons east and west per day.

East 4050 × 4900	19,845,000 ft-tons	
West 4050 × 1607	6,508,350 "	
	26,353,350 "	
Add 10 per cent for slow movements and starts	2,635,335 "	
		28,988,685 ft-tons

Freight:

16,040 tons east per day
10,600 " west " "

East 16,040 × 4900	78,596,000 ft-tons	
West 10,600 × 1607	17,034,200 "	
Total	95,630,200 "	
Add 10 per cent for slow movements and starts	9,563,020 "	
		105,193,220 ft-tons
Total passenger and freight energy per day		134,181,905 ft-tons

$$\text{H.p-hr. per day} = \frac{134{,}181{,}905 \times 2000}{33{,}000 \times 60} = 135{,}537$$

Based on previous detailed studies of similar problems we are safe in assuming 70 per cent efficiency from power station to locomotive wheels = 144,600 kw-hr. per day at the power station
= 52,779,000 " " year " " " "

Requiring, at 210 kw-hr. per bbl. of oil, 251,330 bbl.
Costing, at $0.40 per bbl., $100,530.

NOTE. The 70 per cent average efficiency given above is deduced from the following average all-day efficiencies of the plant as designed:

Transmission line	98 per cent
Conversion apparatus	90 per cent
Contact system (This being the ratio of the average volts—2100, to the generated volts—2400).	87½ per cent
Locomotives	90 per cent

making a net efficiency of 69½ per cent, which for practical purposes has been called 70 per cent.

Since the position of all trains on the track is known with great accuracy from the train dispatcher's sheets, it is expected that substations on which there is no load will be shut down completely until the train dispatcher advises the station operator that a load is approaching his substation. The foregoing accounts for what may be considered a high average conversion efficiency.

NOTE. In order to show how closely to the average the tonnage runs from month to month, the table of tonnages for the fiscal year 1911-12, is given in Appendix L2.

Fig. 7 gives the train diagram for the conditions of traffic under which this estimate is made. It shows only those trains that are running up-hill, no account being taken of the down-hill trains for obvious reasons. Of course this is not strictly accurate because the trains will consume some small energy in supplying air for brakes, etc., and in occasional movements into and out of sidings, but the error in estimating the probable down-hill use easily may be greater than the total energy consumption of the down-hill trains.

From the foregoing train diagram is made the load diagram given in Fig. 6, the method being as follows—As has been stated

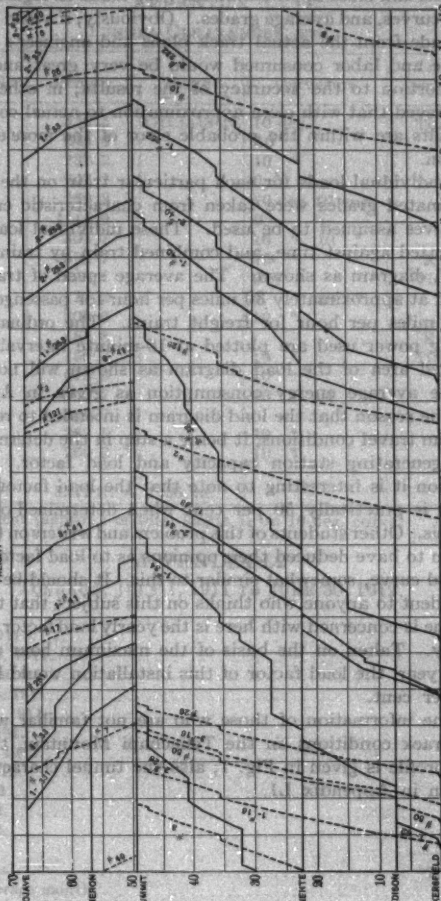


FIG. 7—TRAIN DIAGRAM

previously, in determining the load diagrams from the train diagrams, certain close approximations were made as regards ruling grades, curves, and average grades. Obviously, if a load diagram were made from the actual track plans and engineer's profiles, the time and labor consumed would be very great and out of all proportion to the accuracy of the results; in other words, it is believed that with close approximation to actual conditions the results are within the probable error of the more extended operation.

The individual loads for each particular train on the various approximated grades were taken from characteristic curves of locomotives assumed to be used. These individual loads were then plotted against time, and combined train by train to give the load diagram as shown. The average speed of trains was assumed at approximately 30 miles per hour for passenger trains and 15 miles per hour for freight trains. The ordinates representing power used are plotted at 15-minute intervals. The integrated area of the load diagram as shown will not check with the average energy consumption as given in Appendix K, for the reason that the load diagram is intended to represent maximum travel conditions, it being a step in the determination of the generating station capacity and load factor. In this connection it is interesting to note that the load factor of this diagram is practically 50 per cent when determined on the ½-hour basis. Other students of this problem and writers on this subject seem to have deduced their opinions as to load factors from a selected curve, somewhat similar to this. It should be reasonably evident to anyone who thinks on this subject that the load factor one is concerned with here is the yearly load factor and not the daily. Taken on the basis of the maximum hour and the average year, the load factor of this installation would be close to 20 per cent.

For the information of those who are not familiar with the actual track conditions on the Tehachapi Mountain, the condensed profile is given in Fig. 1; also the tunnel characteristics are given in Appendix L1.

APPENDIX L1

Tunnel Clearances, etc.

Tunnel No.	Length	Height	Curvature	Lining material
1/2	539.5	17ft.to18½ft.	10 deg.	Timber
1	245.8		10 "	"
2	232.2		10 "	"
3	707.7		0	"
4	256.3		10 deg. 05 min.	"
5	1145.9		0	"
6	303.7		10 " 10 "	"
7	532.7		10 "	Rock
8	690		0	Timber
9	426.2		0 " 20 "	"
10	306.6		10 "	"
11	158.8			Rock
12	756.3		10 "	Timber
13	513.8		10 "	"
14	512.7		10 " 04 "	"
15	360.7			"
16	262.5		10 "	"
17	260.9		10 "	"
	8212 ft. =	1.56 mi.		

60 per cent (approx.) of total length is on 10-deg. curve.

APPENDIX L2

Tonnage, July 1, 1911 to June 30, 1912.

July, 1911	564,201
August, 1911	638,665
September, 1911	640,178
October, 1911	666,807
November, 1911	671,708
December, 1911	683,618
January, 1912	688,883
February, 1912	701,846
March, 1912	694,475
April, 1912	666,762
May, 1912	712,251
June, 1912	635,963
Total	7,965,357
Average month	663,780

	Tons	Per cent of average
Minimum month	564,201	85.05
Maximum "	712,251	107.2

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 10, 1913.

Copyright 1913. By A.I.E.E.

THE GULF OF GEORGIA SUBMARINE TELEPHONE CABLE

BY E. P. LA BELLE AND L. P. CRIM

The recent laying of a continuously loaded submarine telephone cable, across the Gulf of Georgia, between Point Grey, near Vancouver, and Nanaimo, on Vancouver Island, in British Columbia, is of interest as it is the only cable of its type in use outside of Europe.

The purpose of this cable was to provide such telephonic facilities to Vancouver Island that the speaking range could be extended from any point on the Island to Vancouver, and other principal towns on the mainland in the territory served by the British Columbia Telephone Company.

The only means of telephonic communication between Vancouver and Victoria, prior to the laying of this cable, was through a submarine cable between Bellingham and Victoria, laid in 1904. This cable was non-loaded, of the four-core type, with gutta-percha insulation, and to the writer's best knowledge, is the only cable of this type in use in North America. This cable is in five pieces crossing the various channels between Bellingham and Victoria. A total of 14.2 nautical miles (16.37 miles, 26.3 km.) of this cable is in use. The conductors are stranded and weigh 180 lb. per nautical mile (44.3 kg. per km.). By means of a circuit which could be provided through this cable by way of Bellingham, a fairly satisfactory service was maintained between Vancouver and Victoria, the circuit equating to about 26 miles (41.8 km.) of standard cable. All communications to points on Vancouver Island north of Victoria were routed through this cable circuit. As a consequence the speaking range from Vancouver to the Island was limited to a few points near Victoria,

and Nanaimo was the extreme limit of commercial service, and conversation was not attempted except under the most favorable conditions. Under some conditions conversation was possible except for the distorting effect of the unloaded cable.

By using the new cable, Nanaimo is made the center of distribution for Vancouver Island. The longest line that will ever be connected at Nanaimo will extend to the north end of Vancouver Island, and will be about 250 miles (400 km.) in length, so it can readily be seen that satisfactory service may be established to any point on Vancouver Island through the new

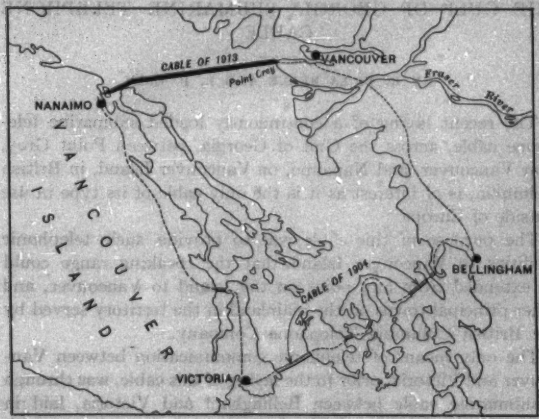


FIG. 1—ROUTE OF CABLES OF 1904 AND 1913. BROKEN LINES INDICATE AERIAL LAND LINES.

cable. It was with the idea in mind of using Nanaimo as the distributing center that the existing route was chosen for laying the cable.

It is quite important to the long life of a submarine cable that a rock bottom and exposure to tidal currents be avoided as much as possible. It is also quite essential that the shore ends be landed in mud or sand and that they be kept buried, at least as far as the low water line. It is believed that the route chosen will prove to be very satisfactory.

The new cable was manufactured by the Henley Telegraph Works, in England, and has the following mechanical properties:

Conductors. Four conductors, each consisting of a central wire, surrounded by twelve wires of annealed copper, having a total weight of 300 lb. per nautical mile (73.4 kg. per km.); total diameter of conductor 0.1385 in. (3.518 mm.).

Loading. One soft iron wire 0.012 in. (0.305 mm.) in diameter, wound round the conductor and having seventy turns per inch (27.6 turns per cm.).

Dielectric. Three coats of best gutta-percha alternating with three coats of Chatterton's compound. Total weight of dielectric per nautical mile 300 lb. (73.4 kg. per km.). Diameter over gutta-percha 0.409 in. (1.04 cm.).

Cabling. Four cores laid around a yarn center, wormed, brass taped and served with yarn.

Armoring. Fifteen galvanized steel wires each 0.192 in. (0.487 cm.) in diameter, separately tarred and served with tarred yarn.

Outer Serving. Two coats of tarred yarn, and two coats of preservative compound.

Diameter. Diameter of completed cable 1.956 in. (4.97 cm.).

Weight. Weight of completed cable, eight English tons per nautical mile (4.38 metric tons per km.).

The same type of armoring was used throughout, and on account of the armor wires each being served with tarred jute, the completed cable was very flexible.

The cable has the following electrical qualities, as measured on 31.3 nautical miles (58 km.) of the completed cable in the factory at a temperature of 75 deg. fahr. (24 deg. cent.). All quantities per nautical mile.

	Conductor resistance	Electrostatic capacity	Dielectric resistance*
	Ohms	Microfarad	Megohms
No. 1 Core	4.004	0.3449	258
No. 2 Core	4.004	0.3455	256
No. 3 Core	4.004	0.3449	268
No 4 Core	4.005	0.3449	274

*After one minute's electrification.

PER NAUTICAL MILE OF LOOPED CIRCUIT

	Cores	Conductor resistance	Electrostatic capacity
		Ohms	Microfarad
Circuit A	1 and 3	8.008	0.1724
Circuit B	2 and 4	8.009	0.1726
Superimposed or phantom circuit on A and B		4.0045	0.3450

The following values were obtained by an eminent independent testing authority on a length of one-twentieth of a nautical mile cut from the completed cable. Results are per nautical mile, and tests were made with sinusoidal current at a frequency of 800 cycles per second, at a temperature of 56 deg. fahr. (13 deg. cent.).

Column A, loop or side circuit cores 1 and 3
" B, " " " " " 2 and 4
" C, superimposed or phantom circuit.

	A	B	C	
Effective resistance R	9.16	9.14	4.69	ohms
Effective inductance L	11.56	11.54	5.45	millihenrys
Effective capacity K	0.1647	0.1662	0.3338	microfarad
Effective leakance S	12.24	11.26	19.84	microhms
Ratio S/K	74.3	67.8	59.4	
Attenuation constant	0.01892	0.01874	0.01966	

The following results were obtained in the laboratory of the manufacturers on the completed length of 31 nautical miles (58.5 km.) coiled up in the iron tank and covered with water, using sinusoidal current at 800 cycles per second, as before.

Circuit	A	B	
Open impedance Z_o	349.35 $\backslash 32°31'$	337.4 $\backslash 33°54'$	Vector ohms angle
Closed impedance Z_c	185.75 $/23°53'$	187.5 $/24°43'$	Vector ohms angle
Characteristic impedance Z	254.5 $\backslash 4°19'$	251.4 $\backslash 4°56'$	Vector ohms angle
Attenuation constant	0.01946	0.01940	

After laying, the cable was tested for dielectric resistance, for capacity, and for conductor resistance. The transmission equivalent was measured in terms of standard cable and tests were made for crosstalk.

SUMMARY OF TESTS AFTER LAYING

	Conductor resistance	Mutual capacity
	Ohms	Microfarad
No. 1 Circuit	8.008	0.175
No. 2 Circuit	8.008	0.174

	Electrostatic capacity	Dielectric resistance
	Microfarad	Megohms
No. 1 Core	0.347	445
No. 2 Core	0.349	451
No. 3 Core	0.351	461
No. 4 Core	0.347	461

The above results are per nautical mile. Dielectric resistance is corrected to 75 deg. fahr. (24 deg. cent.).

The actual length of cable in use is 28.3 nautical miles (52.5 km.) and its mean temperature was 49.6 deg. fahr. (9.8 deg. cent.) at the time the measurements were taken. Speech tests showed a standard cable equivalent of eight miles with zero loop on each end, and 5.75 miles, with 12 miles of standard cable at each end to reduce reflection losses.

The finished cable was shipped from England to Vancouver on the ship *Crown of Galicia*. It was stored in a steel tank while on shipboard and kept under water. The temperature was observed daily throughout the voyage. Upon arrival at Vancouver, it was transferred from the tank in the hold of the *Crown of Galicia* to the hold of the barge *Princess Louise*, from which it was later laid. The actual operation of laying was begun at the Point Grey end at 4 a.m. June 16th, and finished at Kanaka Bay on New Castle Island at 7:30 the evening of the same day. The illustrations herewith show the laying operations in detail. Throughout the entire operation of laying, one pair was under continuous test for insulation resistance, while the other pair was being utilized for communication with the shore. As a matter of precaution the two pairs were interchanged at intervals so that no fault in the dielectric could escape observation for any length of time. While the cable was being laid, conversations were carried on with parties in Vancouver, Victoria, Seattle and Portland. Two tugs were used to tow the cable ship, which was without power of its own. Telephonic communication was maintained with the tugs by means of rubber covered wires strung on the hawser. Observations to determine the location were taken at regular intervals with a sextant, and a log of operations was carefully kept. The tension on the cable was observed by means of a dynamometer, and the amount of cable paid out was read from the rolometer attached to the paying-out drums. With the exception of a light rain in the morning, the weather was excellent, and a number of guests observed the laying operations, which were without accident.

A cable hut is provided at each of the shore ends for housing the protective apparatus and making the connections between the cable and the aerial land lines. The protective apparatus is of the Lodge-Muirhead type, and consists of three reactive coils with four discharge points, located around a central brass disk, which is grounded to the armor wires of the cable. Each of the cable cores is led through a protector of this type, and a fuse is inserted between the protector and the line wire, and also between the protector and the cable. All of the protective apparatus is housed in a waterproof cast iron case.

The two physical circuits provided in this cable were satisfactory in every way and are each equivalent to about 5.75 miles of standard cable. The phantom circuit, however, is not so satisfactory. It is only fair to the manufacturers, however, to state that a satisfactory phantom circuit was not guaranteed. It will be seen that the capacity and leakance of the phantom circuit is just two times as great as in the physical circuits, while the resistance and inductance are about one-half each. This causes the attenuation constant of the phantom to be somewhat greater than that of the physical circuits. There is also some crosstalk between the physical circuits and the phantom, being equivalent to a conversation through about 75 miles (120 km.) of standard cable. Tests for this determination were made with local battery sets, in the cable huts, connected directly to the ends of the cable. This crosstalk is undoubtedly caused by inductive unbalance in the cable. On account of the salt water penetrating to the outside core of the gutta-percha, the wires are shielded from each other electrostatically. Any disturbance that is transmitted from one wire to another must therefore be of an electromagnetic nature. The capacity of the cores in this type of cable depends upon the thickness of the dielectric, and in every case is the capacity from the wire to the ground (salt water), as the sea water penetrates the cable to the gutta-percha. Efforts to decrease the capacity of this type of cable by a paper wrapping under the gutta-percha, in order to increase economically the diameter, have failed because of the moisture content of the gutta-percha being absorbed by the paper.

The uniformity of the capacity then depends upon the cores being exactly of the same dimensions and located symmetrically. It can readily be seen that a slight eccentricity of conductor in the dielectric will change the capacity accordingly.

The inductance of these cable circuits is artificially increased

by a winding of soft iron wire around the copper conductor, which increases the permeability of its magnetic field. This is the well-known Krarup system of continuous loading. The permeability of this wire may be affected in three ways, namely, aging, by straining it beyond its elastic limit, and by permanently magnetizing it. Aging occurs in nearly all iron used in magnetic circuits and the magnitude of the change of permeability varies with the different pieces of iron. It is thus possible that the inductance of the different cores of a Krarup cable might be thrown out of balance by the iron wires aging differently. It is known that the permeability of magnetic iron is affected by straining it beyond its elastic limit. When it is considered that the loading wire is only 0.012 in. (0.305 mm.) in diameter, and that in order to hold it around the copper conductor so that it will remain evenly distributed, it is necessary to apply it with considerable tension, it is more than likely that a considerable amount of this wire has been heavily strained. This is indicated by its appearance. During manufacture the different sections of core were spliced together in such a way as to neutralize as far as possible any unbalances that could be detected at that time. It will be seen that the total capacities and inductances of the different cores are in a fair degree of balance. There is very little danger of the iron wrapping used in continuous loading ever becoming permanently magnetized, as this would require a very heavy current.

It is customary to measure the direct-current insulation resistance of a gutta-percha core at 75 deg. fahr. (24 deg. cent.) and after one minute's electrification. The insulation resistance increases quite rapidly after the initial electrification and only reaches a fairly constant state after some time. This effect, although not well understood, seems to be somewhat similar to the polarization effect of an electrolytic couple. The dielectric resistance so obtained cannot be used to deduce the leakance S for calculating the attenuation constant and circuit impedance. Measurements for this quantity must be made at telephonic frequencies and voltage, and owing to the extremely small quantity of power involved, are exceedingly difficult to make with any degree of precision.

Gutta-percha is rarely employed as an insulator for telephone conductors, with the exception of submarine cables in deep water. While information regarding its various characteristics is not very plentiful, a brief statement of its qualities may be of interest.

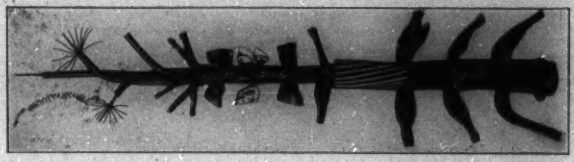
It is composed of pure gutta, rosin and water. It is a vegetable gum secured from certain tropical trees very much the same as India rubber. It is collected by native labor, and shipped in the raw state to the factory where it is prepared for commercial use. The first step in its preparation is to remove all impurities, as far as possible, which is done by boiling in water. It is then put through a masticating machine, after which it is rolled out into thin sheets.

The wire which is to be insulated with gutta-percha is first given a coat of Chatterton's compound, and then a coat of gutta-percha is applied with a sheathing machine, in much the same manner as lead sheaths are applied to the ordinary paper-insulated telephone cable. Additional layers are applied, alternating with layers of Chatterton's compound, until the required thickness of dielectric has been obtained. It should be noted that gutta-percha is not subjected to any process similar to the vulcanization of rubber, but is used in the raw state. It contains no sulphur, and copper wires do not require tinning before being insulated with gutta-percha.

In general, rosin increases the initial insulation resistance of gutta-percha, but if it is present in too great proportions it tends to separate, especially upon exposure to heat and light, and causes cracks to form in the insulation. Ordinary grades contain from five to six per cent moisture. The insulation resistance increases very rapidly with a decrease in temperature, so that at 45 deg. fahr. (7.2 deg. cent.) its insulation resistance is about ten times that at 75 deg. fahr. (24 deg. cent.). If it is heated much above 80 deg. fahr. (27 deg. cent.) it soon softens, and in a completed cable this would allow the cores to become deformed, especially if the cable were subjected to any considerable pressure, such as the lower coils in a cable tank. Instances have been known where the copper conductor by its own weight became so eccentric in the core that a large quantity of the cable was ruined on account of the insulation becoming too thin.

Generally speaking, if different grades of gutta-percha are mixed together, a higher dielectric resistance is obtained, but the fibrous structure is not so good as if one quality were used throughout.

The splicing of a gutta-percha-insulated conductor is one requiring no little skill and care. It is necessary in splicing a four-core cable that the spliced conductors be of equal length, so that no one splice will be subjected to more than normal



[LA BELLE AND CRIM]

FIG. 2.—DETAILS OF CABLE CONSTRUCTION.

[LA BELLE AND CRIM]

FIG. 3.—COILING OF CABLE IN HOLD OF *Princess Louise*.

[LA BELLE AND GRIM]

FIG. 4.—CABLE IN TANK ON BOARD *Crown of Galicia*.

[LA BELLE AND GRIM]

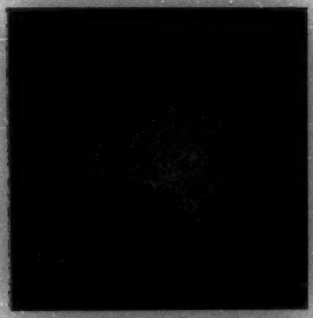
FIG. 5.—PAYING-OUT DRUMS.

[LA BELLE AND CRIM]

FIG. 6.—CABLE LAYING GEAR IN OPERATION.

[LA BELLE AND CRIM]

FIG. 7.—SIDE VIEW OF CABLE SHIP UNDER WAY



[LA BELLE AND CRIM]

FIG. 8.—DISTRIBUTION OF MAGNETIC FLUX IN FOUR-CORE CABLE, CURRENT FLOWING IN PHYSICAL CIRCUIT ONLY.

[LA BELLE AND CRIM]

FIG. 9.—DISTRIBUTION OF MAGNETIC FLUX IN FOUR-CORE CABLE, CURRENT FLOWING IN PHANTOM CIRCUIT.

stress. In splicing the conductors, the ends are scarfed and soldered together. Then the joint is given a close wrapping of fine copper wire, which is also soldered all over. A second wrapping of fine copper wire is then applied in reverse direction and soldered only at the ends. In case the joint was so strained as to break the soldering in the main conductor and the first wrapping of copper wire, this last spiral wrapping would still form a metallic connection across the break. In joining the dielectric, the same number of layers of gutta-percha are applied, alternating with Chatterton's compound, as are used in the manufacture of the core. The gutta-percha is warmed with a spirit lamp until plastic, and is applied with the fingers. The finished splice must not have a much greater diameter than the unspliced core and must show leakance not in excess of a piece of core ten times the length of the splice. Owing to the inability of gutta-percha to stand exposure to moderately high temperature, light and air, it has been the practise among European engineers to splice a piece of rubber-insulated cable on to the gutta-percha below the water level at the shore ends, and thus make the landing with rubber-insulated cable. As it is well nigh impossible to make a perfect splice between rubber and gutta-percha, it is necessary to employ a water-tight junction box if this method of terminating the shore ends is used. No method has yet been found for cementing rubber and gutta-percha together so that the joint will hold for any appreciable length of time. The practise of using rubber insulation for the shore ends was not followed in laying the Point Grey-Nanaimo cable, for the above reasons. The shore ends have been buried from the terminal in the cable hut to low water, and on account of this, will not be exposed to temperature very much above that of the sea water. Sufficient slack has been left in the cable so that in case the ends at the terminals lose their insulating qualities, they may be cut off and the cable reterminated. In this way the ends of the cable may be kept in excellent condition by allowing a few feet extra for the cable reterminating.

In a four-core cable such as is generally used for telephone purposes in deep water, the two opposite cores are used to form each circuit. It is not necessary, if the cores are arranged symmetrically about the center, that the wires be twisted in pairs in order that each circuit will be unaffected by the current flowing in the other. The wires of one circuit do not inter-loop the lines of magnetic force from the other, and each of the wires

is under the influence of equal and opposite electrostatic fields. This latter is not true of a cable submerged in salt water, due to the shielding effect of the salt water. As mentioned before, it will therefore be seen that the two circuits are quite independent of each other both electromagnetically and electrostatically. The same thing is true of the superimposed or phantom circuit, but the results obtained in practise are not so good as with the two physical circuits.

In selecting a design of cable suitable for this service, the choice was practically limited to a four-core gutta-percha cable, loaded either by the continuous or Krarup system, or by the use of Pupin coils. Owing to the depth of water (1300 feet = 396 meters) a paper-insulated lead-covered cable was not seriously considered. The stress during the laying would so strain the cable in passing over the drums and sheaves that there would be great danger of impairing the insulation between the wires. Owing to the highly distortional effect of non-loaded gutta-percha cable, it was necessary to eliminate such a cable from consideration. It remained, therefore, to choose between the two types of loading. It is well known that a coil-loaded cable is quite superior to a continuously loaded cable, or in fact any other design of cable, when electrical qualities alone are considered. The continuously loaded cable is mechanically quite simple and upon its completion is equally as strong as a non-loaded cable such as has been used for telegraph service for years, even at the maximum depth of the ocean. In a coil-loaded cable the only acceptable design of coil so far employed is one which surrounds the four cores of the cable, and which is taken inside the regular cable armor. This causes an increase in the diameter of the cable from two to three times its unloaded diameter, and in spite of precautions which may be taken in the manufacture, these loaded points are the weakest spots in the cable, both electrically and mechanically.

The two best-known examples of coil-loaded submarine cable extend from England to France across the English Channel, and from England to Belgium. The former cable is about 20 nautical miles (37.1 km.) in length, and the latter about 40 nautical miles (74.2 km.) in length. Neither of these cables is laid in a very great depth of water, and both are under the supervision of the British Post Office, which has available cable ships especially designed for the laying and repairing of such cables. The older of these cables has only been in use about three years, and

during this time no serious case of trouble has developed, so that the actual difficulties to be encountered in repairing this type of cable can only be forecasted in view of experience in repairing the non-loaded type.

In order to keep the transmission in a coil-loaded cable at its original quality, it is necessary that the spacing of the coils be kept as originally laid out, allowing only a variation of five per cent. It is quite obvious that this is not true of the continuously loaded type, and any increase in the length would cause an increase in the transmission loss, only in proportion to the increased length of the cable employed.

In case of a fault in deep water, the cable is picked up by means of a grapnel and as soon as it is brought to the surface it must be cut in order to relieve the great strain. One end is retained, and a line is made fast to the other end, which is thrown overboard with a buoy attached. The cable is then picked up until the fault is located and repaired. It is then necessary to splice in a piece of new cable and pay out until the buoyed end is picked up, when as much slack as practicable is taken out and the two ends spliced together. It will thus be seen that a considerable additional length of cable will be introduced in case of a fault in very deep water. In case such a repair was made at a depth of 1300 ft. (396 m.), under the most favorable conditions, it is quite probable that 800 to 1000 ft. (244 to 305 m.) of additional cable would be introduced. As 300 ft. (91 m.) is the greatest allowable variation with coils spaced one nautical mile (1.854 km.) apart, it will be seen that the coil spacing would be badly disarranged and serious reflection losses introduced. It must also be remembered that no gutta-percha cable is manufactured in America and the only submarine loading coils so far manufactured have been made in Europe, and in case extensive repairs were necessitated, it might be necessary to secure special equipment and skilled labor from Europe, while with the type adopted, repairs can be made with the equipment and labor commonly used in repairing telegraph cables.

Comparisons between the two types of loading have been made and much discussed by different authorities, and a comparatively recent paper on this subject by Mr. J. G. Hill[1] summarizes arguments in favor of the two types in a very excellent manner. It is a well-known fact that the two types of cable having the same

1. "The Loading of Submarine Telephone Cables," by J. G. Hill—*Electrical Review* (London), Nov. 29, Dec. 6 and 13, 1912.

transmission efficiency may be produced, the coil-loaded cable at much less expense than the continuously loaded cable. Mr. Hill bases his comparison on two factors; one, that inductance can be added by the continuous method of loading only up to a certain limit, say 20 millihenrys, while by coil-loading, any desired amount of inductance may be added to the circuit; and second, that the ratio R/L, obtainable with the coil-loaded cable, is much less than that obtained in continuous loading. The limit of economic loading depends upon the amount of resistance added to the circuit in increasing its inductance.

The attenuation constant of a cable is unfavorably affected by the addition of resistance. All known methods of increasing the inductance of a circuit, also increase the effective ohmic resistance, and Mr. Hill compares the efficiency of the added inductance in terms of the amount of resistance so added. It has been found that the ratio between the added resistance and the added inductance for continuous loading is about 110, while a good design of loading coil has a ratio of R/L of about 60. These ratios are true only for the amount of inductance used in ordinary practise. The increase in effective resistance, as is well known, is due to the eddy currents and hysteresis losses in the iron of the magnetic circuit. Eddy current losses can be reduced by subdividing the iron. Hysteresis losses depend upon the degree of saturation of the magnetic field, which is kept low in all telephone circuits. Pupin coils employ a toroidal magnetic core composed of a large number of turns of very fine iron wire with some type of enamel insulation. It is possible to employ several layers of fine wire on a continuously loaded cable, and several have been laid which use three layers. The improvement in the magnetic circuit by such subdividing is not so marked as in the coils, and the expense is very much greater. It would seem that future design will show a still greater advantage in the coil-loaded type of cable, as it is probable that the R/L for loading coils can be reduced still more, economically. It might be of theoretical interest to remark that as the effective resistance of a coil-loaded conductor is a function of the frequency, it is therefore impossible to build a distortionless circuit employing iron magnetic fields.

We can therefore summarize the arguments that we considered in selecting the type of cable as follows:

Arguments in Favor of a Coil-Loaded Cable. 1. Could employ smaller conductors, and less gutta-percha, and secure a cheaper

cable for the same transmission equivalent (disregarding terminal losses).

2. Could give the phantom circuit the same degree of loading as the physical circuits.

3. Could add any desired amount of inductance.

4. Aging of the iron cores of the loading coils could not unbalance the circuits.

Arguments in Favor of a Continuously Loaded Cable. 1. Simplicity of construction.

2. Could be laid and repaired like an ordinary gutta-percha-insulated telegraph cable.

3. Short lengths added in repairs do not materially affect the transmission.

4. Not liable to faults at loading coils.

5. Faults could be located more accurately by means of resistance measurements.

6. Is not heavily loaded, and therefore has less reflection losses at shore ends where it joins to non-loaded open wire lines, than would be the case with a coil-loaded cable.

7. Known to be reliable at the greatest depths of water.

It was after due consideration of the above factors that the continuously loaded type was decided upon, and the results obtained have amply justified the selection.

A paper presented at the 285th Meeting of the American Institute of Electrical Engineers, Vancouver, B. C., September 11, 1913.

Copyright 1913, By A.I.E.E.

A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT

BY JOHN B. FISKEN

The substation which forms the subject of this paper was put into service in November, 1910, and is the outcome of seven years' experience gained by the Washington Water Power Company in distributing electric power by means of 60,000-volt lines to the Coeur d'Alene mining district in Northern Idaho.

This substation has been provided for the purpose of supplying three-phase power to the Bunker Hill & Sullivan Mining and Concentrating Company, at 2300 volts. This power is used for all purposes contingent to mining, such as running compressors, pumps, d-c. generators for mine and yard haulage, hoists, saw mills, concentrators, et cetera, and for commercial lighting in the mining towns of Kellogg and Wardner.

As an indication of the evolution of this branch of The Washington Water Power Company's business, it may be stated that when the transmission line from Spokane was put into operation in August, 1903, the substation built at that time for the Bunker Hill & Sullivan mine was equipped with one transformer of 275-kv-a. capacity, whereas the demand now requires three 650-kv-a. capacity transformers. It may be here stated that the introduction of reliable electric power has been the principal factor in making the output of the Coeur d'Alene mining district in lead today the second largest of any district in the world. And not only has this power been of inestimable value to the developed mines of the district, but on account of its low cost and its flexibility and convenience it has enabled prospects to be developed into mines, which without it would have remained dormant for many years.

The location of this substation is fortunate. It is within a distance of 400 ft. (122 m.) from the main transmission lines, which are in duplicate, the branch being provided with air switches to enable it to be connected to either main line. There is a spur from the railroad about 26 ft. (7.9 m.) from the building and at an elevation four ft. (1.2 m.) below the floor level, so that transformers, or other heavy apparatus, can be rolled off the railroad cars and into the building without having to be raised or lowered. The cooling water for the transformers comes from the mine tunnel, the portal of which is at an eleva-

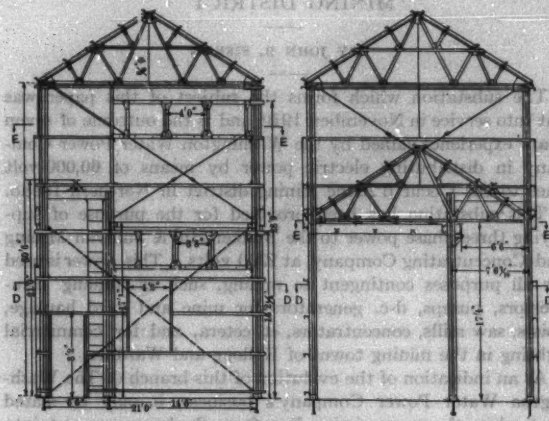


FIG. 1

tion of about 43 ft. (13 m.) above the top of the transformers. The secondary line to the Bunker Hill & Sullivan main switchboard is only about 750 ft. (228.6 m.) in length. These almost ideal conditions are not easily obtained in a rough, mountainous country.

The building consists of a framework of structural steel, covered, both sides and roof, with galvanized corrugated iron, the main columns being supported on concrete footings. The floors are all of concrete, making the building practically fireproof. Figs. 1 and 2 show the details of the steel framework.

[FISKEN]

FIG. 3—FIRST TYPE OF BRICK SUB-STATION

[FISKEN]

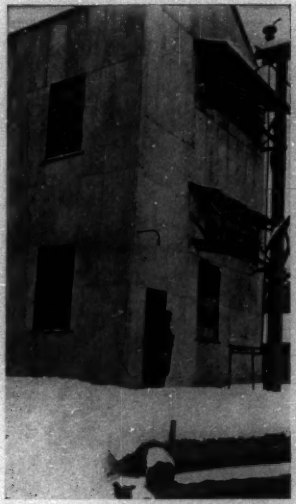
FIG. 4—LATER TYPE OF BRICK SUB-STATION

[FISKEN]

FIG. 5—STANDARD STEEL SUBSTA-TION

[FISKEN]

FIG. 6—BUNKER HILL AND SULLIVAN SUBSTATION, LOOKING NORTH



[FISKEN]

FIG. 7—BUNKER HILL AND SULLIVAN SUBSTATION, LOOKING EAST

[FISKEN]

FIG. 9—TOP OF LIGHTNING ARRESTER HOUSING

This type of building has been adopted in preference to brick, stone or concrete buildings on account of the ease with which it can, should the occasion arise, be taken down and reerected at some other location. The experience of the Washington Water Power Company has shown that such occasions do arise, in a rapidly growing mining country, due to consolidation

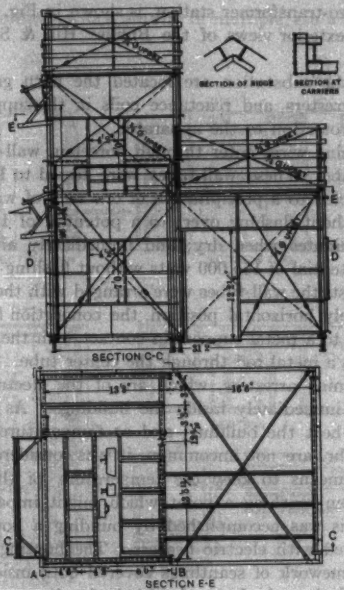


FIG. 2

of adjacent properties and centralization of the works, or to the abandonment of properties which have "played out", or, as in the case of the Bunker Hill & Sullivan mine, to the extensive development of the property.

While the steel type of substation offers no saving in first cost, it has the advantage that if it should have to be moved all that is lost of the first investment is the cost of the concrete

and labor of erection and equipment. This has been demonstrated on several occasions to the satisfaction of The Washington Water Power Company. On the other hand the salvage from a brick building is practically nothing, as the cost of taking it down and cleaning the brick is about all the material is worth. The first type of brick substation is shown in Fig. 3, and a later type in Fig. 4. The first type of steel substation, which is standard for a two-transformer station, is shown in Fig. 5, and Figs. 6 and 7 are exterior views of the Bunker Hill & Sullivan substation.

Outside the substation are located the horn gaps for the lightning arresters, and reactance coils in the supply wires as a further protection to the apparatus.

All incoming wires enter through porcelain wall-tubes set in concrete slabs. These wall-tubes were tested to 135,000 volts when subjected to a precipitation of one inch of water per five minutes without flashing over; to a potential of 155,000 volts for three minutes when dry; and immediately after the last test to a potential of 165,000 volts without flashing over. During these tests the wall-tubes were arranged with their axes in an approximately horizontal position, the connection for potential being made to a metal support in contact with the edge of the disk, and to a metal rod through the center tube.

The lightning arresters, which are of the electrolytic type, are located immediately inside the buildings. As no attempt is made to heat the building, and as temperatures as low as −30 deg. fahr. are not uncommon, it was considered advisable to provide means to keep the temperature of the lightning arresters from reaching a point which might impair their efficiency. This was accomplished by building a housing which can be heated with electric heaters. The housing consists of an open framework of scantlings covered both inside and out with metal lath and plastered with hydraulic cement plaster, the open spaces being filled with loose shavings. To permit of readily removing the arresters, portions of the top of the housing are omitted and openings are left in the front. The openings in the top of the housing are closed after the arresters are in place by means of asbestos slabs, and removable doors built of asbestos slabs strengthened with wooden framework close the openings in front. Fig. 8 shows the details and Fig. 9 gives a general view of the top of the housing with roof insulators and connecting leads of copper tubing.

Fig. 10 shows vertical and horizontal sections of the substation with the apparatus in position.

The main 60,000-volt conductors, which can be opened near their entrance by means of disconnecting switches (see Fig. 11), go through an oil switch to the busbars above the transformers. The oil switch is equipped with a series overload relay in each leg.

The transformers, which are run in multiple, are water-cooled,

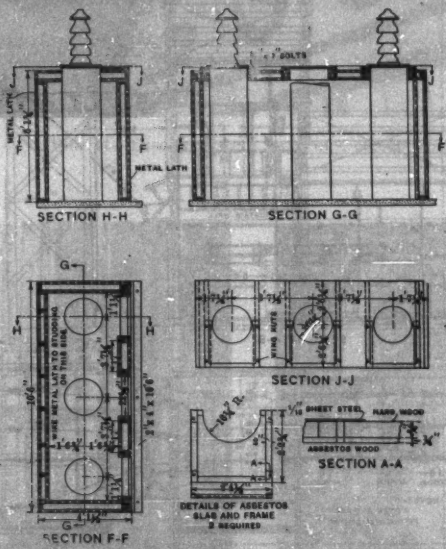


FIG. 8—DETAILS OF LIGHTNING ARRESTER HOUSING

three-phase connected, the primary in Y and the secondary in △, the neutral of each high-tension winding being grounded. Three transformers, of 650-kv-a. each, are used instead of one of greater capacity, for the reason that they were available when the station was equipped and spare transformers of that size are kept on hand; it is expected, however, that some time in the future these will be replaced by larger ones, and the building has been designed to admit of the installation of transformers

up to 2200-kv-a. capacity. The use of water-cooled, three-phase, instead of single-phase transformers was decided upon for several reasons when the first transmission line was built into the Coeur d'Alene country. The cost per kilovolt-ampere at the factory was very much less, and a considerable saving was made in freight. The economy in floor space was also a factor, not only on account of the saving in cost of the sub-

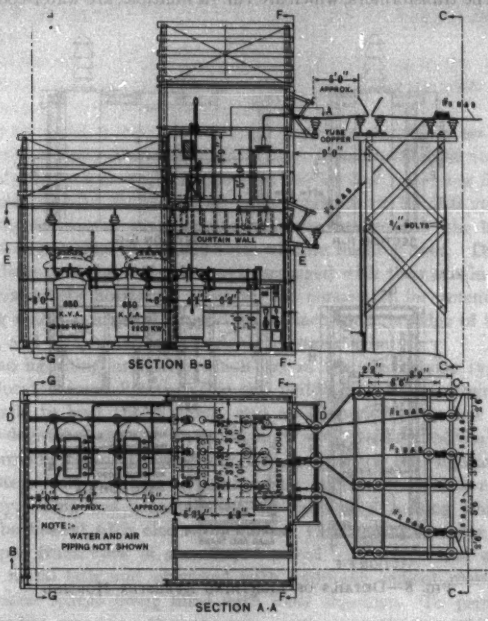
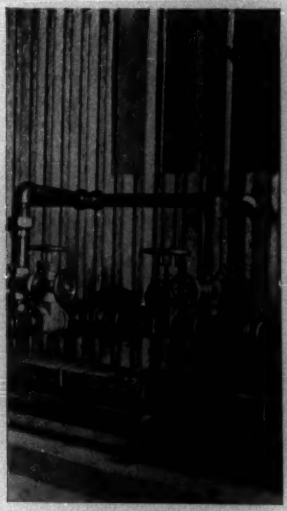


FIG. 10—SECTIONS OF SUBSTATION

station buildings, but owing to the fact that many of the substations had to be located in a canyon where every square foot of available space was valuable, while others had to be located on steep mountain sides. The Washington Water Power Company was among the first, if it was not actually the first company to adopt the three-phase transformer, and the results have been such that after an experience of over ten years,

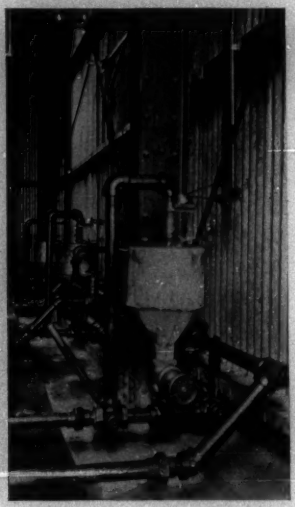
[FISKEN]

FIG. 11—DISCONNECTING SWITCHES, 60,000 VOLTS



[FISKEN]

FIG. 12—INCOMING WATER AND AIR PIPES

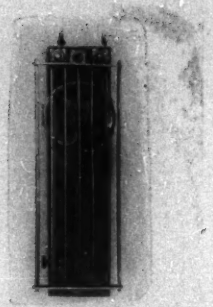


[FISKEN]

FIG. 13—TRANSFORMER PIPING

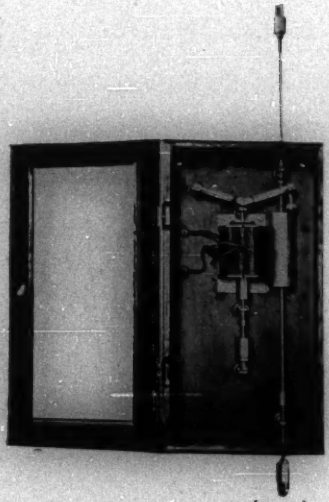
[FISKEN]

FIG. 14—WATER RELAY



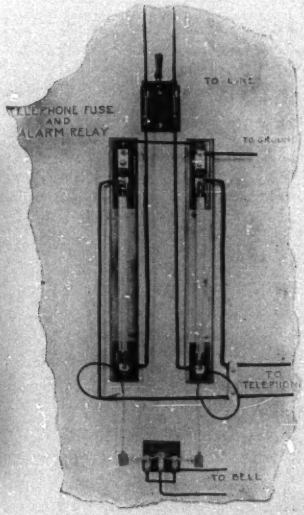
[FISKEN]

FIG. 15—THERMOSTAT



[FISKEN]

FIG. 17—AUTOMATIC TRIP



[FISKEN]

FIG. 18—TELEPHONE EQUIPMENT

not only in the company's substations but in its generating plants, it continues to purchase them.

The cooling water for the transformers is taken from the mine tunnel through a flume to a storage and settling tank, from which it is piped to the transformers. As the normal flow of water is greater than is required, the level in the tank is constant, and a low water alarm is provided to notify the attendant in the compressor room of the mine if for any reason the supply from the tunnel should be cut off. Provision is made for the use of domestic water, but in the dry, hot summer months, when the water is most required, this is very scarce and it is only used in case of emergency. As this mine water carries considerable solid matter in suspension and as all of it is not deposited in the settling tank, a permanent connection is made to each transformer from the mine air line, and at frequent intervals, what solid matter has settled in the cooling coils is blown out by air at a pressure of about 80 lb. per sq. in. (5.6 kg. per sq. cm.). Fig. 12 shows the incoming water and air pipes and Fig. 13 is a view of the piping back of the transformers.

The water is discharged from the transformers normally into the hoppers shown in Fig. 13, but can by means of a three-way valve be discharged directly into the drain pipe.

The secondary of each transformer is connected to the 2300-volt busbars, which are carried along the side of the building to the feeder switches. These switches are attached to the wall of the building and in front of them are set the controlling and instrument panels, ample working space being left between.

As will be seen, the building is arranged to admit readily of extension should the demands of the service require it, all that is necessary being to extend the side walls and roof and move the end back, no changes being necessary in the front.

For the protection of the transformers some special devices have been employed.

To prevent damage, if for any reason the supply of water should fail and the low water alarm in the tank fail to act or receive the necessary attention, a little device which is called a "water relay" is provided. This piece of apparatus, shown in Fig. 14, and as installed, in Fig. 13, consists of a beam having at one end a small bucket and at the other a balance weight which can be moved along the beam. The beam is fulcrumed so that when the bucket is full of water the combined weight of bucket and water overcomes the balance weight and raises it. A vertical rod attached to the beam moves in a vertical

plane and by means of a system of levers causes two metallic points connected electrically as well as mechanically to dip into two cups of mercury. A small hole is made in the bucket through which the water can be drained out, and two binding posts connected to the mercury cups allow for conveniently attaching the wires of the control circuit. This apparatus is mounted on the discharge pipe over the hopper and the water as it comes from the transformers falls into the bucket. This keeps closed the control circuit of which the mercury cups and contacts form a part. If for any reason the water should cease to flow through the cooling coils there would be nothing to keep the bucket supplied, and what water was left in it would run out through the drain hole, thus allowing the balance weight to fall and opening the control circuit at the mercury cups. By varying the size of the drain hole a fairly accurate time element can be introduced. As will be explained later, the opening of the control circuit at the mercury cups trips out the 60,000-volt oil switch, or starts an alarm bell ringing if the switch should fail to open. This apparatus is the result of much experimenting and has now been perfected to such a degree that absolute reliance is placed on it. It has demonstrated its value on several occasions and all water-cooled transformers installed on the system are now equipped with it, those in the substations where there is no constant attendance being arranged to trip out the oil switch, while in the other substations and power houses it calls the attention of the attendant by ringing the alarm bell.

It not infrequently happens that the water supply may be diminished to such an extent as to allow the temperature of the transformer to rise to a dangerous degree and yet prevent the water relay from operating; or an excessive overload may come on without causing the automatic switches to open. In either event the results as far as the transformer is concerned would be disastrous, and to prevent any damage from these causes a thermostat, Fig. 15, provided with suitable binding posts for attaching the wires of the control circuit, is hung in the oil above the windings. This thermostat is made by riveting together two metal strips of different coefficients of expansion and is adjusted so that when the temperature of the oil reaches 65 deg. cent. the control circuit is opened, which, as in the case of the water relay, trips out the 60,000-volt switch or causes the alarm bell to ring.

The control circuit, Fig. 16, is normally closed, is energized

by a secondary generator giving about 6 volts alternating current on the terminals and has in addition to the water relay and thermostats two modified 50-ohm telegraph relays. These relays are in multiple with each other and in series with the water relay and thermostat.

As originally installed, ordinary relays were used, the magnet coils being energized and the armatures held over against the pull of a spring so that the secondary contacts were open. It was found, however, that the constant chattering of the armature due to the alternating current was very hard on the apparatus and made the relays somewhat unreliable. This difficulty was overcome by providing the magnets with two windings of 50 ohms each, one connected in the control circuit and the other connected directly to the generator, the two windings being in opposition to each other. Thus as long as the control circuit remains closed the armature is not attracted, but should this circuit open, the remaining winding energizes the magnet, attracting the armature and closing the relay circuits or the alarm bell and the "auto trip".

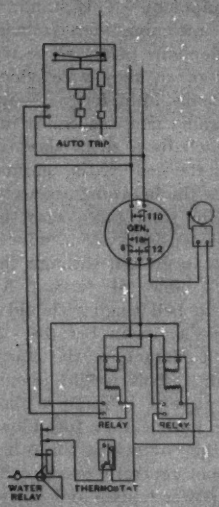


FIG. 16—CONTROL CIRCUIT

The "auto trip", Fig. 17, is a device for tripping the 60,000-volt oil switch. As previously stated, the only relays for this switch are of the series mechanical type, so that no low-voltage connection could be made to them and some other arrangement had to be made.

Between the end of the hand rope which is provided for tripping the switch by hand and the switch tripping mechanism, an iron rod ¼ in. (6.3 mm.) in diameter is introduced. This rod, which is connected to the mechanism by a chain, to give flexibility without stretching, passes through the iron box containing the auto trip and at a suitable location has a collar fastened to it by a set-screw. Above the set-screw and surrounding the rod, which can be moved through it freely, is a heavy weight suspended on a dog attached to a toggle arrangement. The trip coil is located under the toggle joint so that

when it is energized the plunger, which has an adjustable dashpot to provide a time element, is pulled up, striking the toggle joint, releasing the weight and allowing it to fall on the collar, which trips the switch. Owing to the iron rod being free to move through the weight, the switch can be tripped by hand at any time, independent of the auto trip.

The substation is provided with a telephone connected to one of the operating lines, the equipment being temporary, to be changed later to a standard equipment. This standard equipment is shown in Fig. 18. The incoming lines connect to the lower ends of the fuses, the telephone being connected to the upper ends. The fuses consist of an alloy wire which fuses at one ampere, contained in glass tubes 14 in. long. Above the telephone connections are the lightning arresters, consisting of two carbon plates separated 0.01 inch by a small sheet of mica with a $\frac{1}{8}$-inch diameter hole in the center, the ground connections being taken from the top of the lightning arresters. As the telephone lines are carried on the same poles with the 60,000-volt line, any trouble on the high-tension system induces high-voltage surges in them which go to ground through the lightning arresters and in most cases blow the fuses. An alarm device is provided which starts a bell ringing should a fuse blow; this is shown below the fuse tubes in Fig. 18. A short pivoted arm carries on one end a contact for the alarm circuit and on the other a small weight. This weight is suspended from the fuse wire by a short piece of fish line so that the alarm circuit is normally kept open, but should a fuse blow, the weight is allowed to fall, closing the contact at the other end of the arm. This alarm device is not generally used in the substations but is always used in the power houses and patrol stations. In the power houses, instead of ringing a bell a small pilot lamp is lit, which indicates at a glance which fuses are blown. In the patrol stations the value of this alarm device is inestimable. Before its introduction there were several occasions on which the fuses were blown during the night and were only discovered when the patrolman awoke in the morning. Under these circumstances it was impossible for the system operator to call the patrolman, but with the introduction of the alarm device this difficulty has been entirely overcome.

The substation is in close proximity to some valuable mine buildings, which are all wooden structures, and fear was expressed by the manager of the mine that if the oil in one of the transformers should catch fire and the burning oil boil

Name of machine	Number in operation	Size	Length	Diameter	Wi
West Mill No. 1.					
Jig Motors:					
Rolls	3	14 in. x 36 in.	..	..	
Water pump	1	7 in.	..	..	
Elevator	1	..	113 ft. 6 in.	..	16
Jigs	6	4 comp't.	33½ in.	..	25½
Jigs	6	5 comp't	33½ in.	..	25½
Trommels	4	3 to 10 mm.	10 ft.	48 in.	
Elevator	1	..	44 ft.	..	16
Table Motors:					
Elevator	1	..	84 ft. 6 in.	..	16
Huntington mill	2	6 ft.	..	..	
Sand pumps	2	3 in.	..	..	
Sand pump	1	2 in.	..	..	
Frue vanners	28	6 ft.	..	..	
Card tables	25	Model C	..	..	
West Mill No. 2					
Jig Motors:					
Rolls	3	14 in. x 36 in.	..	..	
Elevator	1	..	125½ ft.	..	16
Jigs	12	4 comp't	33½ in.	..	25½
Jigs	1	3 comp't	33½ in.	..	25½
Trommels	4	3 to 7 mm.	10 ft.	48 in.	
Trommels	2	15 mm.	5 ft.	48 in.	
Table Motors:					
Chilean mill	1	6 ft.	..	..	
Hardinge "	1	6 ft.	..	..	
Elevator	1	..	84 ft. 6 in.	..	16
Frue vanners	28	6 ft.	..	..	
Card tables	20	Model C	..	..	
Water pump	1	6 in.	..	..	
Sand pump	1	2 in.	..	..	
Esperanza	1	..	20 ft.	..	4
Feed Conveyor Motor:					
Feed conveyor	1	20 in.	451½ ft.	..	20
Rock House					
Storage Bin Motor:					
Conveyor and distributor	1	..	370 ft.	..	34
Rock House Motor:					
Kennedy crusher	2	No. 5	..	..	
Trommels	4	30 mm.	7½ ft.	48 in.	
Rolls	1	14 in x 36 in.	..	..	
Conveyor	1	..	144 ft.	..	24
"	1	..	140 ft.	..	42
"	1	..	113 ft.	..	24
"	1	..	63 ft.	..	20
Elevators	1	..	59 ft.	..	16

TABLE II

APPARATUS IN BUNKER HILL AND SULLIVAN MILLS, WITH POWER REQUIRED.

Rev. per min.	Feet per minute	Capacity tons per day	Slope	Gal. per minute Approx.	Approx. sizing of feed: On 3 in. ring	On 7 mm.	On 3 mm.	Through 3 mm.	Approx. sizing of discharge: On 7 mm.	On 3 mm.	Through 3 mm.	H.p. each	Total h.p.
75	..	350	..	..	..	46%	44%	10%	15%	45%	40%	19	38
700	..	..	..	2000	..	..	..	..	..	..	..	..	..
43	473	..	..	..	..	..	..	..	..	..	..	..	..
150	..	500	..	..	..	80%	20%	..	..	..	..	3	15
225	..	200	..	..	..	..	..	..	..	..	..	3	3
16	..	950	1 in. to 1 ft.	..	..	..	..	..	..	..	..	3	12
43	473	..	..	..	..	..	..	..	..	..	..	..	..
53	583	250	..	..	..	..	..	..	..	..	..	..	..
71	..	75	..	..	..	..	..	..	..	..	..	18	36
928	..	100	..	..	..	..	..	..	..	..	..	..	15
1282	..	25	..	..	..	..	..	..	..	..	..	..	10
200	3 ft. 11 in.	50	5/16in. to 1ft.	..	..	..	..	..	..	..	..	1	2
240	..	90	..	..	..	..	..	..	..	..	..	1	2
85	..	..	..	..	..	46%	44%	10%	15%	45%	40%	19	38
41	451	..	..	..	..	..	..	..	..	..	..	..	15
150	..	850	..	..	..	..	..	..	..	..	..	3	3
150	..	100	..	..	..	..	..	..	..	..	..	..	2
16	..	..	1 in to 1 ft.	..	..	..	..	..	..	..	..	3	12
16	..	..	..	..	..	..	..	..	..	..	..	3	6
25	..	75	..	..	..	..	..	..	..	..	..	..	30
32	..	40	..	..	..	..	..	..	..	..	..	..	15
45	495	..	..	..	..	..	..	..	..	..	..	..	12
200	3 ft. 11 in.	80	5/16in. to 1ft.	..	..	..	..	..	..	..	..	3	14
240	..	50	..	..	..	..	..	..	..	..	..	1	2
860	..	..	..	2000	..	..	..	..	..	..	..	..	20
1268	..	40	..	..	..	..	..	..	..	..	..	..	15
..	17	200	..	..	..	..	..	..	..	..	..	..	4
..	180	1200	22½ deg.	..	..	..	..	..	..	..	..	..	15
		Capacity tons per hour (Runs 8 hrs. per day)			On 3 in. ring	On 30 mm	On 3 mm.	Through 3 mm	On 12 mm.				
..	300	150	21%	..	..	..	..	..	..	..	..	..	17
475	..	25	..	..	80%	..	..	..	83%	17%	..	15	30
16	..	150	1 in. to 1 ft.	..	..	..	..	..	..	..	..	3	12
150	..	50	..	..	..	90%	..	..	83%	11%	6%	..	16
..	300	150	..	..	..	..	..	..	..	..	..	..	10
..	45	150	..	..	..	..	..	..	..	..	..	..	4
..	300	150	..	..	..	..	..	..	..	..	..	..	4
..	200	50	..	..	..	..	..	..	..	..	..	..	7
23	253	50	..	..	..	..	..	..	..	..	..	..	12

[STEREN—10 1906]

out of the case it would endanger the buildings. To overcome this objection the building inside is banked with concrete and drains are provided to allow the burning oil to flow into a covered cesspool large enough to hold all the oil in one transformer.

The cost of this substation was as follows:

Building (including concrete foundations and floors)	$3,733.00
Electrical equipment (exclusive of transformers)	5,003.00
Transformers installed	11,125.00
Water system for transformers	651.00
Total	$20,512.00

or $10.52 per kv-a.

The annual cost of operating the substation is as follows:

Depreciation (being the sum of the depreciation of each item and being equal to a little over 7% of the total cost)	$1,452.00
Interest at 8%	1,641.00
Taxes	77.00
Maintenance and operating (being the average of the annual cost since the station was put in service)	530.00
Total	$3,700.00

or $1.90 per kv-a.

It should be noted that the small item for operating is due to the fact that the automatic features make it possible to dispense with the services of an attendant. The substation, however, is visited every day by a patrolman who changes the charts of the recording instruments and makes a general inspection.

The maximum demand of the Bunker Hill and Sullivan Company is about 2000 h.p. and Table I shows the connected horse power of motors in the different branches of the mining operations and the percentage of the total.

TABLE I
CONNECTED LOAD OF MOTORS AT BUNKER HILL & SULLIVAN MINE

	h.p.	Per cent of total
Compressors	475	16.1
Mills	965	32.1
Hoists	200	6.7
Pumps	385	13.1
Haulage	438	14.7
Crushers	335	11.2
Other operations	182.5	6.1
	2980.5	100.0

To those who are familiar with the operation of such large mines as the one in question the percentage of motor capacity for driving compressors will no doubt appear small, but this is explained by the fact that a very large part of the air compression is done by water-driven compressors.

The motors in the mills are used for driving a great variety of apparatus and Table II is of interest as showing the different apparatus with the work done by each and the size of motor required. The daily output of the mine is about 1200 tons of ore and there are three mills available to handle it, but Table II merely gives the data of the two newer mills, as the old mill is used only to a very small extent.

The following Table III, which shows the distribution of cost of electric power and light for an average month, is of interest also as showing the cost of this service for the different operations.

TABLE III

DISTRIBUTION OF COST OF ELECTRIC POWER AND LIGHT FOR ONE MONTH

Electric power		Electric light	
Hoist	$218.40	Tramming	$41.10
Pumps	412.80	Hoisting	3.10
Mills	3100.25	Mill	25.40
Mine traction	237.74	Machine shop	0.50
Yard traction	30.40	Saw mill	0.70
Machine shop	11.65	Assay office	0.25
Saw mill	79.10	Blacksmith shop	0.25
Assay office	3.00	Yard	1.10
Compressors	299.10		
Electric light used	72.40		72.40
	$4464.84		

After more than two years' service the results from the operation of this substation have been satisfactory both to the power company and the customer. There have been some interruptions to the service, but considering that the transmission line feeding this station is about eighty miles in length and runs through a rough mountainous country, this has to be expected. During the year 1912 there were fifteen such interruptions of an average duration of fifteen minutes each. The causes were various, such as lightning, limbs of trees blown into the wires, insulators broken by rifle shots and so forth. In addition there were, during the same period, about four interruptions due to trouble on some part of the mining company's installation.

In conclusion the author desires to acknowledge his obligation to Mr. Walter C. Clark, electrical engineer, and Mr. R. S. Handy, mill superintendent, both of the Bunker Hill & Sullivan Mining and Concentrating Company of Kellogg, Idaho; to the former for information given in Table III; to the latter for the information contained in Table II.

DISCUSSION ON "A MODERN SUBSTATION IN THE COEUR D'ALENE MINING DISTRICT" (FISKEN), VANCOUVER, B. C., SEPTEMBER 11, 1913.

W. V. Hunt: I have listened with great interest to the paper read by Mr. Fisken, and I was particularly interested in the design of a substation that could, if necessary, become a portable substation, inasmuch as it could be moved to another district.

I think in some cases we might go further with the design of substations with that idea in view; we have some substations that are more portable than that, as they are built on standard railroad cars, and we can take them around on our system, and I think this idea might be extended to some mining districts, keeping the capacity of the substation within reasonable limits. We may adopt a substation on the lines of the one developed by Mr. Fisken in some districts adjacent to Vancouver.

Frederick D. Nims: I have talked this subject over with Mr. Fisken considerably during the last year or two, and I think his station and one that we might build would be very much along the same lines; I think there are a few points that we cannot agree upon, one being that he leans a little bit too much to three-phase transformers. In putting in a station such as he describes, with three 650-kw. three-phase transformers, personally I would prefer to put in transformers of a slightly higher voltage, connecting them in delta, having an opportunity of running open delta with one transformer disconnected, if the occasion should arise. This is merely a difference of opinion.

I ask Mr. Fisken to what capacity he thinks it is possible to carry the automatic idea. Personally, I do not see any reason why it should not go as far as you like. Also, from the illustrations, it would appear that a single circuit of 60,000 volts goes into the substation. From what distance does that single circuit run over a double-circuit line, or to what extent is the station dependable on a single circuit, in miles?

I have seen the water relay and it is very ingenious indeed, but the comment which I made to Mr. Fisken is, that I think he has gone a little bit too much to automatic devices and not left quite enough to the man who goes around to look after the station.

W. Fraser: I believe that the use of portable substations or semiportable substations will become more usual in the future than it has been in the past. The cost of operation is actually reduced and I think that is what all companies are trying to accomplish at the present time.

Mr. Fisken did not give us the type of the lightning arrester, nor state whether they are charged bi-weekly or daily; I expect it is daily charging, however, because it seems that a patrolman is on the scene, and therefore it might be convenient to charge them daily.

It hink the advantages of the daily over the bi-weekly charging warrant the installation of the daily charging arrester.

C. F. Terrell: I rather question the use of water-cooled transformers for this class of service; the use of self-cooled transformers means a higher first cost, but on the other hand gives greater simplicity and reliability, freedom from troubles that attend equipment for supplying cooling water, and it would probably be possible to have the substation inspected by the patrolman at less frequent intervals.

L. G. Robinson: The improvement of the automatic substation is undoubtedly going to be a great boon to the railway men who have the electrification of trunk lines at heart.

A great deal of fault was found with the high cost of electrification of trunk lines, and a good deal of that high cost is due to the permanent nature of the substations which have to be built for the purpose. Many features were responsible for this high cost of permanent stations, and principally among them were the idea of continuous service and substantial construction for the high factor of safety recommended by Prof. Karapetoff—a high factor of safety of course is always accompanied by heavy and expensive construction—and I think we can all admit that a high factor of safety in regard to automatic substations can be attained with the acquirement of these automatic features. The station does not have to be built upon heavy lines, of solid concrete; the B. C. Electric Railway Company has succeeded in building a substation which can be carried about on wheels, and Mr. Fisken has succeeded in building a substation which can be moved about at a minimum of expense. Together with this comes the idea of automatically cutting out faulty lines in order that operation may go on uninterrupted. That, I believe, up to the present time has been considered an impossible feat. I know that companies with which I have been connected years before this have operated under great difficulties from this particular feature—they have not been able automatically to cut out high-voltage transmission lines.

I agree with Mr. Nims that a good deal of responsibility should be placed upon the operator, and we must depend upon his " personal equation " so to speak; when the operator finds difficulties there usually is a time element sufficient for him to make up his mind whether he will hang on or cut loose, and that, as a rule, in the past has been the safest procedure—his balancing the cost of interruption against the cost of damage from hanging on.

J. A. Lighthipe: Are you attempting to use telephone transformers between your high-tension line and your telephone? We have in Los Angeles two portable substations of 750 kv-a. capacity, on a heavy 15-ton truck, and we pull this truck all over the country roads, sometimes in the case of emergency with an automobile truck; it has been of the utmost service to us

in helping out some of our substations with burned out transformers. It is also very valuable for conventions and illuminations and things of that sort, where there is for a short time, a week perhaps, a very heavy illuminating load in a certain portion of the town where it is not provided for, except with high potential loads.

A. A. Miller: This matter of automatic substations is attracting an increasing amount of attention. Some of you have undoubtedly read the paper, which was presented by Mr. Summerhayes at a comparatively recent meeting of the Institute, which paper appears in this volume, p. 1685, describing an automatic synchronous converter substation used in the city of Detroit. That station has in it apparatus which is occasionally looked upon as being somewhat difficult to operate, but notwithstanding these difficulties, the automatic starting, synchronizing and adjusting are said to be successfully accomplished, and the synchronous converter made to carry its proper share of the load; all of this being done by means of the single alternating-current circuit provided for supplying power to the substation.

It is reasonable to predict that a somewhat extensive effort will be made to perfect automatic apparatus, and to weed out any defects that may exist, which are only to be discovered by continued use and diversified application, and after the reliability of the equipment and the practicability of the idea are thoroughly established, we can rationally expect considerable use of automatic substations.

There may come a time when such substations will be used in railway trunk line electrification, but the reliability of the assembled parts, working as a whole, must be pretty thoroughly demonstrated before we can expect such application.

Portable railway substations have been successfully used for some years. They involve, in nearly all instances, alternating-current transformers, for reducing to the proper voltage for the rotating equipment required for direct current, generally of 600 volts potential. Sometimes synchronous converters are used in such portable substations, and sometimes motor-generator sets, depending upon the individual preferences of the engineer selecting the equipment and the exigencies of the particular application. I believe that portable alternating-current power substations, both single-phase and polyphase, can be used to great advantage by many power companies. The field for such outfits is surely enlarging rapidly, and the moderate voltage transmission lines, or more properly termed, intermediate voltage distributing lines, are now penetrating many farming and agricultural districts, a class of business not particularly sought heretofore. The result is an increasing number of relatively small substations, the total weight of the apparatus involved being no unwieldy amount. Many of these substations are of the outdoor type, and the form of

construction used makes it possible to provide for easy disconnection of the permanent apparatus, and the quick substitution of a portable equipment. It seems to me this idea is entirely practicable, and that the portable alternating-current substation is bound to become a very handy tool for the power companies.

R. W. Pope: In speaking of the developing of automatic stations and machinery, it occurs to me that a recent law of the state of Washington requiring an additional man at substations might stimulate the invention of automatic devices so that instead of one man there would be no man in attendance.

In visiting a station of this kind attended by one man I happened to glance at the instructions for resuscitation and the name of the nearest doctor to be called, and it occurred to me that, possibly, was one of the reasons why the law was being agitated requiring a second man to be in attendance—in case of the disability of the other one.

The development of the automatic telephone system, I think, is one that might be well studied. Of course the conditions are entirely different. Another instance is the automatic block signals of the railroad companies. The manual system has to a large extent been displaced by the automatic, it having been found that the latter is particularly reliable compared with the attendance of an operator.

R. F. Hayward: The question of the design and operation of transformer substations for large high-tension distribution systems is of very great importance on the Pacific Coast, where wages of operators are very high.

Where operators are employed in transformer stations, it is generally necessary to employ three shifts, and often, as a matter of personal safety, a second man on a shift is employed. If this sort of thing were done for anything but large and important transformer stations, it would run up the operating costs of the distributing system so much that no profitable business could be done in a scattered district.

The time was when current from 2000-volt lines was served to customers through the medium of transformer stations, but now outdoor transformers are in very general use on 12,000-volt distributing systems, which are operating with as much ease and economy as the older 2000-volt systems. Consumers are connected at any point on a 12,000-volt line, through the medium of 12,000-volt transformers placed on poles.

It is only a step from 12,000 or 20,000 volts to distribution at 60,000 volts in much the same manner.

The tendency at the present time is to treat the transformer as part of the line, and if 60,000-volt transformer installations are developed along the lines of Mr. Fisken's design, I do not think it will be very long before a 60,000-volt distribution system can be tapped for service at any point where the demand may occur. The only difference between 60,000-volt and 12,000-

volt installations will be that the units dealt in will be larger in the former than in the latter.

The demand for the supply of power to mines and smelters has been one of the principal causes of the rapid development in long-distance transmission during the past fifteen years. The exacting requirements of the power supply for these purposes have taught operators their most important lessons in giving continuous service.

But of all the lessons learned in the West, the greatest seems to me to be that mechanical strength in line construction, and simplicity of arrangement of switches and connections, will go much further towards continuous service, than duplication of lines, switches and transformers with complicated connections.

Simplicity of connections—whether it be in the generating station, transmission line, or transformer station and distributing lines—is, I believe, the keynote to success in giving continuous service.

V. Karapetoff: This question of delta versus Y connection seems never to lose its interest and it is one of these questions that I do not believe will ever be settled, because the conditions of operation are changing, and the apparatus, the safety, and the reliability desired are also changing with the progress of the art. Personally, I believe that this connection—delta-Y—probably with considerable impedance between the neutral and the ground, is a condition that is applicable to a great many transmission systems, notwithstanding I have found systems that operated delta-delta or Y-Y, and I should like to hear some expression of opinion from those who have the most recent experience as to how the matter stands now.

Mr. Fisken mentions an automatic device for indicating when the fuse wire blows out. Some years ago I was connected with a large transmission company in the East and we had this trouble. Some branch lines on a 60,000-volt circuit were protected by copper fuse wires about 16 ft. (4.8 m.) long, placed in rubber tubes, and at night one of these wires would blow, and a little town or factory would be without light or power and the question was put to me to find some kind of indicator that would notify the nearest patrolman about this occurrence. So I went to the principal manufacturers of this kind of apparatus and suggested all kinds of devices that they could furnish, but one of the representatives finally told me, "You do not need any complicated apparatus, all you need is to attach a weight to your wire so that when it blows the weight drops and closes a circuit that rings a bell in the patrolman's cabin." That was a simple idea, and it did me a great service.

John B. Fisken: Mr. Hunt suggested portable substations on flat cars. I wonder if Mr. Hunt has ever been in a mining district? If we could only get an aeroplane that would lift a 650-kilowatt transformer up to one of our substations it

would be a great help. We have one or two substations where we have as much as 30 or 35 per cent grade to get material up. There is much to be said, however, in favor of the substations on flat cars or on wagons if the country is suitable.

Now, our distribution is not entirely mining. Out of 550 miles (167.6 km.) of 60,000-volt lines, I suppose more than half of it is in farming country with substations scattered all over it, and therefore there is no doubt that the flat car substation might be a very good adjunct to our business; the unfortunate part of it is that the "pickings" are awfully thin. In order to make anything at all we have got to keep down our investment, and when we make our rates we have it understood that we will do the best we can to give a constant service, but we cannot undertake to keep spare transformers in every station, or even go to the expense of maintaining a substation on a flat car. We do keep spare transformers at important points ready for shipment, and we can load a transformer and easily have it started on the road in about two to three hours.

Referring to Mr. Nim's discussion, I do not see any reason why we should go to the expense of hauling three transformers up a mountain side when we can haul one. The weight per kv-a. of three transformers is greater, the space required for them is greater, and when you have to excavate in a mountain side to get some place to set them so they won't roll to the bottom that is quite an item. There is one advantage that Mr. Nims points out, that is, in the event of a burn-out in one transformer, if your connections are delta-delta you can cut out one and run open delta. The three single-phase transformers have six points of weakness—they have six entrance bushings; the three-phase transformer has three, which cuts down the liability of trouble to that extent; but the prime reason why we adopted the three-phase transformer was that our first 60,000-volt line was built into this mining country. Twelve years ago we did not know anything about it, we had nothing to guide us, and the factory engineers recommended three-phase transformers; we took their advice and after ten years of operating experience we have never seen any reason for changing our plans. Where we have three three-phase transformers, we might substitute three single-phase transformers, but we use these three-phase transformers in all our stations, and in many places we only have one transformer, which would mean, if we used single-phase transformers in these stations, that our other spare apparatus would not be available.

Mr. Nims asked the question as to what extent the automatic idea could be carried. My opinion is that there is no limit, it can be carried to almost any extent.

Another question was about the length of the single circuit. This station is 400 ft. (121.9 m.) distant from the main lines, which are in duplicate. The two lines, up to a certain point, follow different routes, on different rights-of-way; at a point

about twelve miles from this particular substation they come together. At that point we have a 60,000-volt switching station, equipped with oil switches, electrically controlled. There we can, by putting the two lines on the same bus at one of our stations, switch the load from one line to the other in case of repairs, which we do frequently. In case of trouble of course we can either switch at this particular switching station or we can transfer the branch line by means of the air switches to either of the main lines. At a point some twelve miles beyond we have another 60,000-volt switching station of oil switches, so that we have considerable flexibility. The duplicate line has not been used to any extent except for repairs. The question of the length of a shut-down in the mines, provided it does not extend over a long period, is immaterial. A large part of the load is in the concentrators. If the power goes off, the concentrator is choked and it has to be cleaned out and started over again, so that the question of whether it is off for 15 minutes or two hours is not very material; the big loss to the mining company is in getting started again.

Mr. Nims suggested that there is too much left to the automatic features, and not enough to the attendant. I do not know whether this contention is right or not, but the attendant claims that he has too much to do; he has to take care of a line that rises to an elevation of about 3000 ft. (914 m.) above where his station is located—there is no road, but there is a rough trail, and he has to go up there five miles (8 km.) very frequently; he has another line about 8 miles in length to take care of, and a third line about the same length, so that the attendant is very seldom at the station. His house is only a few hundred feet away, so that when he is at home he is available; but the station is designed to do without even this attendance; all that we require of him is, as I have said, to change the charts on the recording instruments and make a general inspection of the plant. I think, for that reason, all the automatic features I have outlined are necessary. I might state that in the early days what really started us on working out these automatic features was an occurrence that happened at this same plant, although at that time it was an old substation. I got a call one Sunday morning about six o'clock, telling me the transformer 275 kv-a. at Bunker Hill was burned out. I had just time to jump into some clothes, make a rush and catch the morning train. I reached there about one o'clock and was met by one of the men, who said it was all right. He said "The water stopped running and the transformer got hot." I went down and looked it over, everything was all right; but that was the time when it occurred to me that it was necessary for us to have some means of protecting our transformers in case of a recurrence of a shortage of water, and the "auto trip" or "water relay" was the result. The first water relay we built was a very crude affair, which has gone through a number of stages before we finally adopted our present type.

In answer to Mr. Fraser I would state that the lightning arresters are of the electrolytic type, and are charged daily. The patrolman usually gets back home at night; if he does not he telephones in to one of the mining company's men to charge the arresters; but as a rule he attends to them himself.

Mr. Terrell questioned the use of the water-cooled transformers, and his contention I think rather well founded. Unless there is a water supply under gravity, I do not favor the use of water-cooled transformers, and in our practise we are getting away from them. Our first transformers used in the Coeur d'Alene country were all water-cooled. Our experience now is that up there it is the hardest thing in the world to get water. The mining companies actually pump the water for the concentrators two or three times; after the water has gone through the mill they catch it and pump it up again, so that we have been compelled on that account to get away very largely from the water-cooled transformers; but whenever a supply of good water under pressure can be obtained the saving in the cost of handling a water-cooled transformer as against an air-cooled certainly justifies the use of the water-cooled transformer, especially where you have to haul them up the side of a mountain.

Mr. Robinson suggested automatic substations for railway electrification. If you gentlemen ever come to Spokane, and I hope some day you all will, you will have an opportunity of seeing automatic substations on an electric railroad. The Inland Empire Railway system covers about 100 miles (161 km.) of single-phase railway where the substations are entirely automatic. I am not very familiar with the apparatus there, but I do know that I have never seen any attendant. As a general thing substations are located close to a depot, and the agents, when they are not telegraphing or making out waybills or doing something else, go across and look at them; they have worked out the automatic substation for railway electrification.

In regard to our chairman's question, we are using many telephone transformers. Our incoming telephone lines to the Spokane office—we have six or eight of them—are all equipped with telephone transformers; the main generating plants are equipped with telephone transformers; on such substations as I have outlined we provide a stool, which is nothing more or less than a high-tension insulator with a platform on top of it, and a man stands on that when he is telephoning.

I think I have answered our chairman's remarks with reference to a substation on a truck, in talking on Mr. Hunt's remarks.

Mr. Pope is laboring under a misapprehension; the Washington code does not require two men in each station, although it is true that a bill was introduced at Olympia last winter calling for two men. The reason, so far as I know, for requiring two men in each station had no reference to safety; it was simply to make jobs. Mr. Hayward touched on the question of two

operators in a station. We have one station in Spokane, which is our high-tension substation where our lines come in from our outside plants. At that station we have one operator on shift only, and the other operator is in his house (they both live in cottages provided for them alongside the substation) so that if help is required and the operator on duty is able to go for the help he can get it. There is no reason why he should ever have any trouble so far as the electrical arrangements are concerned, as that station is made about as "fool-proof" as it can be made. The switches are all remote control, and the disconnecting switches are handled with long insulated rods, and the only case where he might require help would be in case he should faint or be taken sick; so far as any question of electrical risk is concerned that is practically eliminated. Mr. Hayward's remarks with reference to the reliability of service over one line I think are well taken. We supplied the Coeur d'Alene country from 1903-1908, I believe it was, on one line. We went in there when all the developed mines were running either on water power or on steam; since the day we started giving service I do not believe there has been one single piece of steam apparatus going into that district. The few steam plants that they had, if they are not in the junk pile, are ready to go; the water power of course they use, because that saves them a little money, but very little; so I think we have demonstrated that you can give service over one line that will satisfy a mining community. I am very glad indeed to know that Mr. Hayward endorses my views on the three-phase versus the single-phase transformers.

I am going to dodge Prof. Karapetoff's suggestion of taking up the question of delta versus Y, it is too big; we could argue all day and never get any result. I will say this, that our prime reason for adopting Y on the high-tension side is the fact that we reduce our strains on all the apparatus by grounding our neutral at the generating plants. We have a stress due to 34,700 volts from line to ground. I believe that that is worth a whole lot, and of course doing that prevents a delta-delta connection. We do not use any resistance in our ground connection. We started ten years ago with grounds all through our system; experience has rather tended to indicate that is wrong, and we are now removing the grounds everywhere except at the power plant; at the power plant we expect to keep our grounds, and we expect to have them dead grounds without any resistance; if a line is in trouble the sooner we know it the better, because we can get out and fix it.

I was very much interested in Prof. Karapetoff's statement about the visit to the manufacturer who told him how to arrange his telephone lines to give the indication in case of fuse blowing. I wish I had known that manufacturer, because it would have saved us a whole lot of worry.

The rate for power in the Coeur d'Alene district is $3 per

kv-a. per month, based upon the maximum kilovolt-amperes used in each month, and in addition a charge of one-half cent per kilowatt hour for the kilowatt-hours used in each month. For a one-year contract there is no discount; two-year contract 10 per cent; three-year contract 15 per cent; five-year contract 25 per cent; the Bunker Hill & Sullivan Concentrating Company is working on a five-year contract, so from that the rate can be figured.

J. A. Lighthipe: What is the length of time required to install an oil transformer, to replace the burned-out one; that is, to dry out and fill with oil? You spoke of the kv-a. capacity. What capacity charge is taken for them on the kv-a. or the kilowatt capacity?

J. B. Fisken: We take the assumed voltage of 2300 and measure the amperes. As to the time required to change the transformer in the case of a burn-out, it is a little hard to answer because it depends altogether on where the burn-out is. In our more improved substations we have spare transformers. Now, in the Coeur d'Alene country we can get one into service in about three hours.

A paper presented at the 286th Meeting of the American Institute of Electrical Engineers, New York, October 10, 1913.

Copyright 1913. By A.I.E.E.

TUNGSTEN LAMPS OF HIGH EFFICIENCY—I

Blackening of Tungsten Lamps and Methods of Preventing It

BY IRVING LANGMUIR

While the transformation of electrical energy into heat or even into mechanical energy has for many years been accomplished with efficiencies well above 90 per cent, the artificial production of light has been notoriously inefficient.

The first carbon incandescent lamps had a specific consumption of five to six watts per mean horizontal candle, but these were gradually improved over a long period of years to about 3.1 watts per candle, until finally by the use of the metallized filament a specific consumption of 2.5 watts per candle was reached commercially. Since the introduction of the metallized carbon filament, progress with other types of lamps has been comparatively rapid, and at the present time the most efficient commercial incandescent lamp, the lamp with a tungsten filament, has a specific consumption of from one to one and a quarter watts per candle in the ordinary sizes.

Notwithstanding this decided improvement, we are still far from the theoretical maximum of efficiency that would be attained if all the energy of an electric circuit were converted into visible light.

Drysdale (*Proc. Roy. Soc.* 80, 19 (1908)) has given for the specific consumption of a source of white light of perfect efficiency the value 0.10 watt per candle, and for a source of monochromatic yellow-green light the value 0.06 watt per candle. Ives (*Astrophysical Journal* 36, 322 (1912)), however, gives values very much lower than this; namely, 0.012 watt per candle (800 lumens per watt) for yellow-green light.

The luminous efficiency of the ordinary tungsten lamp lies therefore somewhere between 1 and 6 per cent.

It is well known that tungsten lamps can be run at voltages much higher than their rated voltage, and that in this way extremely high efficiencies may be obtained, but that the life of lamps run under these conditions is so short that the increased cost of renewals more than offsets the saving in electrical energy. It is readily seen that the limit of the commercial efficiency of tungsten lamps is therefore not determined by the melting-point of the tungsten. In fact, if the temperature of the filament is raised to the melting-point, the specific consumption for a period of a few seconds may be as low as 0.20 watt per mean horizontal candle.

The causes which have made it necessary to operate tungsten lamps at such relatively low efficiencies as that corresponding to one watt per candle have been little understood. It seemed, therefore, that an investigation of the phenomena occurring in tungsten lamps, carried out with a view of reaching a clear understanding of the causes of the failure of the lamps, might possibly open the way to the discovery of methods by which the efficiency could be greatly improved.

The present paper is a description of some experimental and theoretical work, extending over a period of many years, which has now resulted in the production of a new type of tungsten lamp; a lamp which will give a life of more than 1000 hours, at a specific consumption in the neighborhood of 0.50 watt per candle.

INVESTIGATION OF CAUSE OF FAILURE OF ORDINARY TUNGSTEN LAMPS

Ordinary tungsten lamps fail, in general, in one of two ways; namely, either by breakage of the filament, or by blackening of the bulb. In ordinary practise the useful life of the lamp is considered to be the time which the lamp burns before its candle-power has fallen to 80 per cent of its original value, or until the filament breaks, in case this occurs while the candle power is still above 80 per cent.

The breakage of the filament was a very serious factor in the early tungsten lamps, as the filament material was extremely brittle. This difficulty has now been overcome by the production of ductile tungsten wire* and by better methods of mounting the wire in the bulbs, so that lamps can now be made which are

*Coolidge, Trans. A. I. E. E. Vol. XXIX, p. 961, (1910)
Fink, Trans. Amer. Electrochemical Soc. 17, 229, (1910).

so strong that a blow is more likely to break the bulb than the filament.

The life of ordinary tungsten lamps, except those of low wattage (40 watts and less), is at present practically determined by the rate at which the candle power decreases. The main cause of this decrease is evident by mere inspection of a lamp which has run several hundred hours. It is due simply to the blackening of the inner surface of the bulb. It is true that the candle power of the filament itself changes somewhat during its life, but this change, on the whole, is an increase in candle power, rather than a decrease. Careful measurements show that during the first few hours running there is usually a slight increase in candle power owing to some change in the surface of the filament which causes greater emissivity of light, or to a slight increase in the conductivity of the filament which leads to an increase of the current and therefore a higher filament temperature. On the other hand there is a tendency towards a lowering of the candle power during the latter part of the life owing to the decreasing diameter and consequent fall in temperature of the filament. Both these causes are insignificant in their effect, as compared with the blackening of the bulb.

The reason for the limited life of the larger sizes of tungsten lamps when run at a specific consumption of one watt per candle, and therefore the reason that higher efficiencies could not be obtained in practise, was evidently the blackening of the bulb.

The cause of this blackening was the subject of much speculation. The prevalent opinion seemed to be that in a normally operated lamp it was due to disintegration of the filament, caused by the presence of traces of residual gas, whereas in lamps run at much more than their rated voltage it was perhaps caused by evaporation. Others, however, considered it due to leakage currents of electricity (Edison effect) across the space between the positive and negative end of the filament. It is well known that discharges through gases at low pressures, cause a marked disintegration of the cathodes. Still others were of the opinion that the blackening of the bulb was due primarily to evaporation of the filament.

In the manufacture of carbon incandescent lamps, it had been found necessary to use a relatively high vacuum, as otherwise the lamps were found to have a very short life. That is, the bulbs blackened rapidly or discharges occurred between the two ends of the filament, finally resulting in the formation of an arc which destroyed the lamp. Various attempts had been made

to prevent the blackening by the introduction of gases at various pressures in the lamp. For example, Edison (U. S. Patent 274,295, March 20, 1883) proposed introducing nitrogen or cyanogen at relatively high pressures, into lamp bulbs, for the purpose of preventing the electric discharge between the positive and the negative end of the filament. In this way he hoped to prevent blackening. These attempts, however, were completely unsuccessful, and it can be readily shown in the case of a carbon lamp, run at say 3 watts per candle and containing nitrogen at atmospheric pressure, that the filament loses weight more rapidly than when run in a vacuum at the same specific consumption. Similar experiments with cyanogen, or even cyanogen mixed with nitrogen, always give lamps which, when run at 3½ watts per candle, give a much shorter life than that of similar lamps with evacuated bulbs run at the same specific consumption.

At a later date, in order to account for this failure to obtain good lamps without a vacuum, the theory was advanced that the presence of a chemically inert gas in a lamp caused a rapid disintegration of the filament by a mechanical "washing," the idea presumably being that the rapid motion of the gas molecules striking against the surface of the filament caused a disintegration of the filament. The general experience of those engaged in the manufacture of lamps did not bear out this theory and it was therefore gradually superseded by others in which the disintegration of the filament was considered to be due to chemical or electrical action of residual gases, rather than to simple mechanical "washing."

In the commercial production of lamps it was found necessary at first to use mercury pumps for the exhaustion of the lamps; mechanical pumps were not good enough. Later it was found possible to obtain a sufficiently good vacuum with mechanical pumps, which by that time had been considerably improved, by introducing red phosphorus into the stems of the lamps and by volatilizing this phosphorus into the lamp just before sealing off, and at the same time heating the filament to a much higher temperature than that at which it was to run normally. It should be pointed out that not only was it necessary to use some such special method of exhaust, but in order to obtain lamps of good life, the bulbs themselves had to be heated to a high temperature during the exhaust, in order to drive off any gases condensed on the surface of the glass. It is interesting to notice that the lamp manufacturers had adopted these precautions in obtaining a high vacuum long

before the necessity for them was realized by most scientific investigators engaged in work with high vacuum.

When the lamp factories began the manufacture of tungsten lamps, they found that much greater precautions were needed in the exhaustion of these lamps than had been necessary for the ordinary carbon lamps, and many improvements in the methods of exhaustion were adopted.

Unless all this care was taken to obtain the best possible vacuum, there were striking evidences of the presence of residual gas in the lamps after they were sealed off. For example, if the normal voltage of the lamp was suddenly applied, a flash of blue glow appeared. Gradually, after a few flashes, this discharge would disappear. This was taken to indicate that the vacuum had been "cleaned up" by the discharge. A similar action of an electric discharge is known in Geissler tubes and X-ray tubes.

In carelessly exhausted lamps, the blue glow would often persist, gradually getting worse, until the lamp "arced across," destroying the filament.

The effect of a poor exhaust was thus to cause the lamps to arc across during the aging process, or to cause them to blacken prematurely.

The general factory experience thus confirmed the opinion that the blackening of the bulb was due primarily to minute traces of residual gas, or to electrical discharges within the lamp.

Much evidence had also gradually accumulated in this laboratory showing that even remarkably low pressures of gases often produced very rapid blackening of the bulbs. A brief account of the early work along these lines has been presented before this Institute by Dr. W. R. Whitney (TRANS. A. I. E. E., Vol. XXXI, p. 921, 1912).

Various attempts to improve the life of lamps by obtaining a better vacuum than usual, had not been very successful. This failure, however, could not be taken as proof that a better vacuum would not improve the life. In the first place, it had been found that during the running of the lamp the vacuum gradually improved after sealing off ("clean-up" effect), the pressure finally reaching a value probably lower than that directly obtainable by any of the well known methods of exhausting. Yet even where we had pressures lower than would be indicated by the most sensitive vacuum gages, we often had clear indications that the blackening of the bulb was due to imperfect exhaust. It seemed quite possible,

therefore, that there might remain, in lamps, minute traces of some gas or vapor which we had not yet learned to remove by our usual methods of exhaust. This residual gas might easily be the cause of the gradual blackening of the bulbs.

Since the pressures were too low to measure, we had no way of knowing definitely whether one method of exhaust was better than another, so that any failure to improve the life by a new method of exhaust might simply mean that the vacuum had not been improved.

It seemed, therefore, that the question as to whether a better vacuum would give a better lamp could only be settled by a direct investigation of the cause of the blackening.

Two lines of attack were decided upon:

1. Study of the sources of gas within a lamp.
2. Effects produced in lamps by various gases.

To facilitate this work, an elaborate piece of vacuum apparatus was built consisting of an improved form of Töpler (mercury) pump, a sensitive McLeod gage and a vacuum oven in which lamps could be heated and exhausted without being subjected to atmospheric pressure from without. Provision was made for the introduction at will of small quantities of any gas to the lamp. Special apparatus was devised by which gas analyses could be made with extremely small quantities of gas evolved within the lamp. For example, it is possible with this apparatus to make a quantitative chemical analysis of a single cubic millimeter of gas and determine the following constituents: oxygen, nitrogen, hydrogen, carbon dioxide, carbon monoxide and argon.*

Sources of Gas within the Lamp

There are four sources of gas within the lamp bulb: first, residual gas left by evacuation; second, gas given off by the filament; third, gas from the lead-in wires or the anchors; and fourth, the gas given off by the glass.

1. *Residual Gas.* The mechanical pumps ordinarily used in exhausting lamps produce a vacuum of about 0.001 mm., according to the McLeod gage. This is probably about the pressure of the non-condensible gases left in the lamp. Besides this, however, there must be some water vapor and oil vapor, and if the filament has been lighted during the exhaust, as is usually the case, there will be some carbon monoxide, carbon dioxide, and

*For a brief description of this apparatus and the methods of analysis employed, see *Journal American Chemical Society*, Vol. 34, 1912, pp. 1310 and 1313.

hydrogen produced by the action of the filament on the vapors. Probably most of these gases are nearly completely removed, or precipitated on the walls of the bulb, by the clean-up that occurs when the phosphorus is volatilized into the lamp and a blue glow made to occur. The final pressure, just after sealing off, is usually in the neighborhood of 0.001 mm. or less.

2. *Gas from the Filament.* The prevalent opinion, as expressed generally in scientific literature, is that metals when heated to very high temperature in vacuum, evolve very large quantities of gas. For example, in a recent article, Prof. J. J. Thomson (*Nature*, 91, p. 335, 1913) says: "Belloc, who has recently published (*Ann. de Chimie et de Physique* (8) 18, p. 569) some interesting experiments on this subject, after spending about six months in a fruitless attempt to get a piece of iron in a state in which it would no longer give off gas when heated, came to the conclusion that, for practical purposes, a piece of iron must be regarded as an inexhaustible reservoir of gas." Thomson's own experience is quite similar.

That the effect of the presence of gas in the metal is considered of importance in connection with the disintegration, is evident from the following quotations from J. J. Thomson's book on "Conduction of Electricity through Gases" (1906 edition). On page 215, he says: "The facts just mentioned suggest that the gas absorbed by the platinum and slowly given off when heated plays an important part in the carriage of the electricity from the wire."—"The emission of absorbed gas from the platinum is, however, according to Berliner (*Wied. Ann.* 33, p. 289, 1888), closely connected with the disintegration of the platinum wire which takes place when the wire is kept glowing and which is made evident by a deposit of platinum or platinum oxide on the walls of the tube and a diminution in the weight of the hot wire: the carriers of the electricity might thus be the dust or vapor of platinum escaping from the wire." Then, on page 216: "There is thus a close similarity between the laws of disintegration of the wire and those of the leak of positive electricity from it."

On page 550, in speaking of the gases given out by the cathodes of vacuum discharge tubes, he says, in discussing some work of Skinner (*Phys. Rev.* 21, p.1, 1905): "The amount of hydrogen that can be got out of a cathode in this way is very large; thus, from a silver electrode 0.15 cu. cm. in volume, Skinner obtained about 2 cu. cm. of hydrogen at atmospheric pressure,

without any indication that the supply was in any way exhausted."

The first few experiments (see *Jour. Amer. Chem. Soc.* 35, 105, 1912) on the gases evolved from the filament of a tungsten lamp also seemed to show the presence of inexhaustible supplies of gas within the filament. Later work proved, however, that this gas was not actually evolved from the filament, but was produced from the decomposition by the filament of water vapor or hydrocarbon vapors present at extremely low pressure in the bulbs. It was finally found that with small filaments, such as are used in lamps, the gas evolved by heating is not more than from three to ten times the volume of the filament. By thoroughly cleaning the surface of the wire before heating, the amount of gas is usually not over half as great. The surprising fact was observed that at least 90 per cent of the gas was given off within a few seconds on first heating the wire to a temperature exceeding 1500 deg. cent. At a temperature below 1200 deg., however, the gas is given off only very slowly, if at all. The gas consists of about 70 to 80 per cent carbon monoxide, the remainder being mostly hydrogen and carbon dioxide. The total amount of gas evolved from the filament of a 40-watt lamp, if liberated in the lamp after sealing off, would produce a pressure of from 0.006 to 0.02 mm.

3. *Gas from Lead-in Wires and Anchors.* In many of the larger lamps, where the leads or anchors become very hot, there are often clear indications that the gas evolved from this source has a marked effect on the life, particularly on the tendency to arc across during aging. In the experimental lamps made with small sizes of wire, the quantities of gas obtained from this source were found to be too small to measure.

4. *Gas from the Bulb.* On heating bulbs of 40-watt lamps (volume about 250. cu. cm.) for three hours to a temperature of 200 deg. cent., after having dried out the bulbs at room temperature for 24 hours by exposure in a good vacuum to a tube immersed in liquid air, the following average quantities of gas were given off:

200 cu. mm. water vapor
5 cu. mm. carbon dioxide
2 cu. mm. nitrogen.

These are the quantities of gas, liberated by the heating, expressed in cubic millimeters at room temperature and atmospheric pressure.

By raising the temperature of the bulbs from 200 deg. to

350 deg., an additional quantity of water vapor was obtained, so that the total now became

300 cu. mm. water vapor
20 cu. mm. carbon dioxide
4 cu. mm. nitrogen.

A subsequent heating of the bulbs to 500 deg. cent. caused the total amount of gas evolved to increase up to

450 cu. mm. water vapor
30 cu. mm. carbon dioxide
5 cu. mm. nitrogen.

At each temperature the gas stopped coming off the glass after a half hour of heating, only to begin again whenever the temperature was raised to a higher value than that to which the bulb had been previously heated.

It therefore seems that even by heating the bulb to 500 deg., not all of the water vapor can be removed, but it does seem probable that after this treatment the amount of water vapor that can come off a bulb at ordinary temperatures must be extremely small.

This study of the origin of the gases within a lamp thus led to the following important conclusion:

The amounts of residual gas, together with all the gas that is given off by the filament and its supports, are quite insignificant as compared with the gas on the inner surface of the bulb. Furthermore, the great difficulty of completely removing the gases from the glass makes this source particularly troublesome in incandescent lamps. We see that the gases likely to be present or given off in an exhausted lamp are, in the probable order of their importance: water vapor, carbon dioxide, hydrocarbon vapors, hydrogen, carbon monoxide, nitrogen and, when phosphorus is used, various phosphorus compounds.

Effects Produced in Lamps by Various Gases

Small quantities (up to 0.1 mm. pressure) of various gases were let into lamps sealed to the special exhausting system and their behavior during the operation of the lamps was noted. The phenomena observed were extremely varied in character, each gas producing very specific effects. In all cases (except argon) a marked clean-up of gas occurred under proper conditions. These effects have been studied in great detail and are forming the basis for a series of publications from this laboratory on chemical reactions at very low pressures. In the present paper only a very brief outline of the results will be given.

*Hydrogen.** This gas cleans up (disappears) in a lamp bulb in four distinct ways. Relatively large quantities (20 to 50 cubic mm.) of hydrogen are driven on to the bulb when the filament is at relatively low temperature (1500 deg. or more). This hydrogen is particularly active chemically (atomic hydrogen) and will react even at room temperature with many reducible substances. Moderate heating of the bulb will cause a large part of it to escape from the glass again. Since water vapor in the bulb is decomposed by the filament to form hydrogen and an oxide of tungsten, there is nearly always a considerable amount of active hydrogen stored up on the bulb after the lamp has been running some time.

The amount of heat carried away from a filament by hydrogen at low pressures, say 0.001 mm., although many times greater than with any other gas, was found to be entirely negligible compared with the heat radiated from the filament. The cooling effect of such pressures of gas, therefore, has no appreciable effect on the life of lamps.

Dry hydrogen in lamps was never found to have the slightest tendency to produce blackening of the bulbs. That is, the bulbs never blackened more rapidly than if the filament were run at the same temperature in a vacuum. Subsequent experiments have proved that this is true from low pressures up to atmospheric pressure.

Oxygen.† At all temperature above 1000 deg. this gas reacts with tungsten to form the yellow oxide WO_3, no matter how low the pressure of the oxygen may be. The oxide distills off the filament and deposits on the bulb, but owing to its light color the deposit is invisible when the amount of oxygen is less than 100 to 200 cu. mm. Oxygen therefore never produces blackening of the bulb.

Nitrogen.‡ There are three ways in which this gas cleans up in a lamp, each being an exceptionally interesting phenomenon in itself. With voltages above 40 volts and pressures above 0.001 mm. the nitrogen cleans up, provided the filament temperature exceeds 2000 deg., and causes an attack on the negative end of the filament, producing a brown deposit of tungsten nitride, WN_2, on the bulb. Except where the amount of nitrogen that cleans up is much larger than could possibly be present in an ordinary lamp, this gas never causes any discoloration of the bulb.

*See Langmuir, *Jour. Amer. Chem. Soc.* 34, 1310, (1912).
†Langmuir, *Jour. Amer. Chem. Soc.* 35, 105 (1913)
‡Langmuir, *Jour. Amer. Chem. Soc.*, 35, 931, (1913).

Carbon Monoxide. This gas behaves almost exactly like nitrogen. At low pressures it never produces perceptible blackening of the bulb, although at higher pressures it may slowly give a slight deposit of carbon under certain conditions. The results, however, clearly indicated that traces of carbon monoxide such as might exist in lamps, could not be responsible for the blackening.

Carbon Dioxide. This gas attacks the filament and produces carbon monoxide and an oxide of tungsten, without producing any perceptible blackening.

Water Vapor. Even very low pressures of water vapor react with the tungsten filament in a lamp to produce hydrogen, and cause rapid blackening of the bulb. Thus a lamp made up with a side tube containing a little water which is kept cooled by a freezing mixture of solid carbon dioxide and acetone (−78 deg. cent.) will blacken very rapidly when running at normal efficiency, although the vapor pressure of water at this temperature is only about 0.0004 mm.

The fact that lamps exhausted at low temperature (say 100 to 200 deg.) blacken so rapidly during life, together with the fact that water vapor is the principal gas removed from the bulb by heating, indicate that the water vapor is responsible for the short life under these conditions.

It is rather surprising that water vapor should have such a marked effect when either of its constituents, hydrogen or oxygen, acting alone, produces no blackening.

The explanation of the behavior of the water vapor seems to be as follows:

The water vapor coming into contact with the filament is decomposed, the oxygen combining with the tungsten and the hydrogen being evolved. The oxide distills to the bulb, where it is subsequently reduced to metallic tungsten by atomic hydrogen given off by the filament, water vapor being simultaneously produced. The action can thus repeat itself indefinitely with a limited quantity of water vapor.

Several experiments indicated that the amount of tungsten that was carried from the filament to the bulb was often many times greater than the chemical equivalent of the hydrogen produced, so the deposit on the bulb could not well be formed by the simple attack on the filament by water vapor.

Another experiment demonstrated that even the yellow oxide, WO_3, could be reduced at room temperature by atomic hydrogen. A filament was heated in a well-exhausted bulb containing a low

pressure of oxygen; this gave an invisible deposit of the yellow oxide on the bulb. The remaining oxygen was pumped out and dry hydrogen was admitted. The filament was now lighted to a temperature (2000 deg. K)* so low that it could not possibly produce blackening under ordinary conditions. In a short time the bulb became distinctly dark, thus indicating a reduction of the oxide by the active hydrogen. Further treatment in hydrogen failed to produce any further darkening, showing that the oxide could only be reduced superficially.

Methane. This gas was decomposed, producing hydrogen, while the carbon was taken up by the filament, as was indicated by the resulting change in the electrical resistance. At very high temperatures the carbon distilled out of the filament again. No visible blackening of the bulb occurred in the experiments with methane.

Argon. The behavior of argon was very interesting. Except with high voltages on the filament and very low pressures of argon, no clean-up of this gas could be observed, even on heating the filament up to its melting-point. The slight clean-up which was observed at high voltages was limited in amount. All of the gas which did disappear could be recovered by heating the bulb.

The presence of argon at pressures above 0.005 mm. and below 1. mm. causes a very large Edison effect and a very rapid blackening of the bulb and attack on the negative end of the filament. The deposit occurs mostly behind the anode, showing that the tungsten atoms in this case are negatively charged.

Although these pressures of argon may cause serious blackening of bulbs, yet the experiments indicated that this is not ordinarily the cause of blackening in well-exhausted lamps. The amount of blackening seemed to depend primarily on the Edison effect caused by the argon, rather than the presence of the gas itself. As the pressure was decreased, the Edison effect decreased even more rapidly, and apparently disappeared entirely, long before a degree of vacuum was reached which could readily be obtained with the pump. It seems extremely improbable that the amounts of argon which might exist in an ordinary lamp could perceptibly affect the Edison current or the rate of blackening.

Higher pressures of argon, close to atmospheric pressure, do not cause either Edison effect or blackening.

*The letter *K* is used to denote temperatures on the Kelvin scale, (absolute temperatures).

Effects of Other Gases. Many other gases and vapors, such as chlorine, bromine, iodine, sulfur, phosphorus, phosphine, hydrochloric acid, etc., were tried, but in no case did these gases produce blackening of the bulbs. If great care is not taken in these experiments to have the gases extremely dry, very marked blackening will result.

Contrary to earlier experiments, it was found that mercury vapor in a lamp did not cause blackening if the voltage was low enough so that no serious Edison effect occurred.

Attempts to Eliminate Water Vapor

This study of the effects produced by various gases led to the conclusion that if the blackening of bulbs of ordinary lamps was caused by imperfect vacuum, then it must be due to water vapor and the further removal of water vapor would markedly increase the life of the lamps. The problem of improving the efficiency of lamps thus assumed more definite form.

Experiments were next undertaken to detect the presence of water vapor in lamps after they had been exhausted at high temperature. It was found on lighting the filaments of lamps which had been exhausted at 200 deg. and then cooled to room temperature, that there was a steady but slow *apparent* evolution of hydrogen from the filament. However, in some lamps exhausted at 350 deg., there was barely a trace of gas evolved under similar conditions. This evolution of gas served as a measure of the rate at which water vapor diffused off the surface of the glass. It proved unreliable as an accurate measure of the water vapor, because of the clean-up of the resulting hydrogen.

Lamps were next exhausted in the special vacuum oven, so that the temperature of the bulb could be raised during exhaust to a temperature about 100 deg. higher than that otherwise attainable. A good mercury pump was used and care was taken to remove the last traces of mercury vapor, water vapor and carbon dioxide, by placing between the lamp and the pump a trap immersed in liquid air. The lamps were exhausted from one to three hours under these conditions. The filaments were heated to high incandescence to drive off gas. The lamps were sealed off when the pressure by the McLeod gage read about 0.00005 mm. These lamps were put on life test and compared with other lamps made under factory conditions.

The unexpected result of this work was that the life of the lamps exhausted with all these precautions was not materially

better than the *best* of the lamps made regularly in the factory. The life of the lamps could certainly not be improved on the average by more than 20 per cent by such methods.

In order to make sure that traces of water vapor were not evolved from the bulb, under the influence of perhaps radiation from the filament, or some other such cause, some lamps exhausted like those described above were run at an efficiency of about 0.7 watt per candle, with the bulbs completely immersed in liquid air during their entire life. Some similar lamps, exhausted in the same way, were run for comparison with their bulbs at room temperature. A third set was run with the bulbs heated continuously in an oven to about 150 deg. cent. The life of all three sets of lamps was practically identical. Previous tests had shown that lamps exhausted in the ordinary way, when kept at 150 deg. during life, gave a very much shorter life than lamps run at the ordinary temperature. These special methods of exhaust therefore did not improve the life of the lamp above that of an ordinary lamp run under normal conditions, but they did make it possible for a lamp to run with the bulb at a high temperature without serious impairment of its life. This seemed to demonstrate that even the complete removal of water vapor from the lamp bulb would not lead to a very radical improvement in the life of the lamp, although the presence of minute traces of water vapor certainly did cause a marked decrease in the life.

The conclusion to be drawn from all of the foregoing work is that the blackening of the bulbs of ordinary well made and well exhausted lamps is *not* caused by imperfect vacuum.

Among all the causes of the blackening that have been suggested, the only one that remains is evaporation of the filament.

Evaporation of Tungsten

To test out whether or not this was the correct explanation, many experiments were undertaken to determine the rate of loss of weight of tungsten filaments when run at various temperatures in lamps. It was found that in lamps with filaments run at the same temperature the loss in weight was proportional to the surface of the filament and independent of the size of the bulb. The temperature coefficient of the rate of loss of weight was extremely high, as would be expected if it were proportional to the vapor pressure of the metal.

Furthermore, the actual measurements at various temperatures

agreed remarkably well with the rational formula for vapor pressure

$$\log P = A - \frac{B}{T} - C \log T$$

From some simple considerations of the kinetic theory of gases, it has been possible to calculate from these data the actual vapor pressure of tungsten at various temperatures. These results have been published in the *Physical Review* (Vol. 2, p. 329, 1913). It is of interest to give here simply the results at a few temperatures:

Specific consumption watts per candle	Temperature (absolute)	Vapor pressure mm.
1.0	2400 deg. K.	0.000,000,05
0.4	2800	0.000,03
0.2 (melting-point)	3540	0.080
(boiling-point)	5200	760.

Experiments with lamps exhausted at a low temperature have shown that the temperature coefficient of the rate of blackening is much lower than in well exhausted lamps. Thus, lamps exhausted at 100 deg. and run at say 5 watts per candle, often blacken nearly as quickly as similar lamps run at 2 watts per candle, although the rate of evaporation in a good vacuum would be very different. This serves to show clearly the radical difference between the two kinds of blackening.

METHODS OF PREVENTING THE BLACKENING OF BULBS

Having now shown that the blackening of ordinary tungsten lamps is caused by evaporation of the filament, the problem of increasing the efficiency of the lamps becomes a very definite one.

Introduction of Gases at High Pressure. Although in the past it has usually been found that the presence of a high pressure of gas causes an increase in the rate of disintegration of a heated metal,* yet if we know, as we now do in the case of tungsten,

*For example, see a recent paper by J. H. T. Roberts, on "The Disintegration of Metals at High Temperatures," *Phil. Mag.* (6), 25, pp. 260 (1913). He gives evidence that the disintegration of platinum and iridium is due to the formation of a volatile endothermic oxide and not to evaporation. In a future paper the present writer will show that at least in the case of very highly heated platinum in oxygen at pressures as low as 0.1 mm., the rate of loss of weight is due entirely to evaporation and is independent of the pressure of oxygen, although all of the platinum which evaporates from the wire combines with the oxygen to form the oxide PtO_2.

that the phenomenon is simply one of evaporation, then we have every reason to believe that the presence of a chemically inert gas will reduce this evaporation. We have seen that low pressures of gases (except water vapor and argon) do not produce any perceptible blackening of the bulb, and therefore produce no disintegration in the ordinary sense. Most gases react chemically with tungsten at high temperature, but hydrogen, nitrogen, argon, and mercury vapor seem to be chemically inert towards it.

In the manufacture of tungsten filaments it was for a long time the practise to sinter the filament thoroughly by heating it to a high temperature in hydrogen or in a mixture of nitrogen and hydrogen. If care were taken to avoid air or moisture in the "forming gas" the filaments would stand heating for a long time in these gases, which indicated that they were at least relatively chemically inert.

Whether the loss in weight at a given temperature was actually greater or less than in vacuum could not be determined from these rough observations. To test this out, a lamp was made and filled with carefully dried and purified hydrogen at atmospheric pressure. The filament was run at the same temperature as that of lamps running at one watt per candle. The heat lost from the filament by convection was so serious that actually 17 watts per candle were required to maintain the filament at this temperature. This lamp, however, ran for more than 360 hours without showing any blackening of the bulb, or any greater loss of material from the filament than would have been the case in vacuum at the same temperature. This result was very striking, as the bulb was running so hot that the life of a filament in vacuum, in a bulb at the same temperature, would have been very short indeed. Subsequent experiments fully confirmed the first one, and showed that even in the presence of hydrogen at atmospheric pressure, the loss of weight of tungsten was much less than in vacuum. The loss of heat, however, was so great that it would be entirely impracticable to make a lamp with the tungsten filament in hydrogen at high pressure.

Subsequent experiments showed, however, that the heat conductivity of hydrogen at very high temperature was abnormally great—much greater than would be expected from the ratio of its heat conductivity to that of other gases at room temperature. This is due to the fact that at high temperatures hydrogen becomes dissociated into atoms.*

*Langmuir, *Journ. Amer. Chem. Soc.*, 34, 860, (1912).

Experiments were next tried with tungsten filaments in mercury vapor. It was found here that the heat loss by convection is extremely small—in fact, so small that a filament could be run for a period of a minute or so, at least, at a specific consumption of 0.23 watt per candle. Even the first experiments showed that the presence of the mercury vapor very greatly decreased the rate of evaporation.

Experiments were then tried in nitrogen at atmospheric pressure. Nitrogen was found to be entirely inert towards the tungsten, and to conduct so little heat that with a fairly large diameter filament the specific consumption was as low as 0.24 watt per candle, at a temperature close to the melting point of tungsten. The rate of evaporation was found to be much less than in vacuum.

For tungsten filaments in these three gases, hydrogen, nitrogen and mercury vapor, the "washing" theory certainly did not apply. On the contrary, instead of increasing, they actually very materially reduced the rate of evaporation.

The next point to be determined was whether the decrease in evaporation was sufficient to offset the heat lost by convection. Because of the presence of the gas, the temperature of the filament was run considerably higher than in vacuum, in order to obtain the same efficiency. Whether or not the rate of evaporation in gas at this *higher temperature* would be less than the rate of evaporation in vacuum at the same efficiency, is a point to be determined only by experiment.

A careful study was therefore undertaken of the laws of heat convection from filaments at high temperature in various gases, since the knowledge on this subject was extremely meager. Experiments were made with platinum wires in air, with platinum wires in carbon dioxide and in hydrogen, and with tungsten wires in hydrogen, nitrogen, mercury vapor and argon.

It was shown* that the heat loss varies with the temperature, according to a simple function of the heat conductivity of the gas; and that it varies with the diameter of the wire according to a rather complicated equation, which, however, accurately expresses the relation between diameter and heat loss. This work indicated that the heat lost by convection increases at high temperatures rather slowly with increase in temperature in the case of nitrogen and mercury vapors, but very rapidly in the case of hydrogen. Further, it was shown that the heat loss from

*Langmuir, TRANS. A. I. E. E. XXXI, p. 1011, (1912)
Langmuir, *Phys. Review*, 34, 401, (1912)

very small wires, say 0.001 in. in diameter, is not very greatly different than that from wires several times this diameter. In other words, it was found that it is much more nearly correct to say that the heat loss by convection from small wires is independent of the diameter, than to say that it varies proportionally with the diameter.

According to the formulas developed in the course of this work, the heat loss from wires of any size in any of the ordinary gases at any temperature could be calculated.* In this way,

Specific Consumption (in Watts per Candle) of Tungsten Filaments in Nitrogen at Atmospheric Pressure, as Compared to that in Vacuum

Absolute temp.	In vacuum	Diameter in inches						
		0.001	0.002	0.005	0.010	0.020	0.050	0.100
2400°	1.00	4.80	3.13	2.02	1.59	1.35	1.18	1.11
2600	0.63	2.53	1.71	1.14	0.93	0.81	0.72	0.69
2800	0.45	1.54	1.07	0.74	0.62	0.53	0.50	0.49
3000	0.33	1.00	0.71	0.50	0.43	0.39	0.36	0.35
3200	0.26	0.70	0.51	0.37	0.33	0.30	0.28	0.27
3400	0.21	0.52	0.39	0.30	0.26	0.24	0.23	0.22
3540	0.20	0.45	0.34	0.27	0.24	0.22	0.21	0.21

Specific Consumption (in Watts per Candle) of Tungsten Filaments in Mercury Vapor at Atmospheric Pressure, Compared to that in Vacuum

Absolute temp.	In vacuum	Diameter in inches						
		0.001	0.002	0.005	0.010	0.020	0.050	0.100
2400	1.00	2.30	1.77	1.38	1.24	1.16	1.10	1.07
2600	0.63	1.30	1.03	0.84	0.78	0.72	0.67	0.67
2800	0.45	0.84	0.68	0.57	0.53	0.50	0.48	0.47
3000	0.33	0.57	0.47	0.40	0.36	0.36	0.35	0.34
3200	0.26	0.41	0.35	0.30	0.28	0.28	0.27	0.21
3400	0.21	0.32	0.28	0.25	0.23	0.23	0.22	0.22
3540	0.20	0.29	0.25	0.23	0.22	0.21	0.21	0.20

the accompanying table was prepared, which gives the calculated relation between the watts per candle and the temperature for filaments of various diameters of tungsten in nitrogen, and in mercury vapor.

It is readily seen from these tables that the loss of efficiency

*It makes relatively little difference whether the wires are placed vertically or horizontally. The heat lost *by convection* is usually 5 to 10 per cent less when the wire is vertical than when it is horizontal.

(at constant temperature) due to the introduction of a gas at high pressure is very much greater for filaments of small size, than for the larger ones, so that with wires of the sizes ordinarily used in lamps the temperature would have to be raised excessively in order to obtain a specific consumption of even one watt per candle. Thus in nitrogen a filament of 0.001 inch diameter (the size ordinarily used in a 20-watt, 110-volt lamp) would have to run at 3000 deg. to give one watt per candle. At this temperature of filament, the life of the ordinary lamp would be about 20 minutes, or about one fifteen-hundredth as long as that when running normally at one watt per candle in vacuum.

With filaments of larger diameter (0.005 inch and more), the loss of heat by convection is not nearly so serious, so that, if the rate of evaporation of the metal is very largely reduced by the presence of the gas, it should be possible to raise the efficiency considerably without shortening the life.

The advantages of a large diameter filament can be practically obtained by coiling a smaller wire into a tightly wound helix or otherwise concentrating it into a small space.

The further development of this type of lamp will be described in the second part of this paper.

Changing Location of the Deposit. In lamps with a very high vacuum, the atoms of tungsten as they are given off from the filament by evaporation, travel in straight lines until they strike the bulb. As they are electrically uncharged (this has been demonstrated by experiment), the field produced by the filaments has no influence on the location of the deposit. Since the light from the filament also travels in straight lines, according to similar laws, it follows that in a high vacuum the deposit always collects most on those portions of the bulb where the greatest intensity of light passes through the glass.

In an imperfect vacuum, especially in the presence of argon, the tungsten atoms tend to become negatively charged and thus often deposit on the bulb very irregularly.

With pressures of nitrogen less than 50 mm., the brown deposit of nitride is distributed over the bulb in much the same way as the tungsten deposit in ordinary lamps. At higher pressures than this the effects of convection currents become apparent, and an increasingly large part of the evaporated material is carried to the upper part of the bulb. At atmospheric pressure this effect is very striking, the bulb on a level with the filament usually remaining perfectly clear, while a dark deposit

gradually forms on the portion of the bulb (or supports) directly above the filament.

This fact is of great importance in connection with lamps containing high pressures of gas. Not only does the gas decrease the rate of evaporation, but it may be made, by proper design, to prevent entirely the blackening of those parts of the bulb that transmit the light.

Summary

1. The efficiency at which the larger sizes of tungsten lamps may be profitably run, is limited principally by the blackening of the bulb.

2. It has usually been considered that the blackening of ordinary lamps was due very largely, if not entirely, to the presence of residual gases. The evidence which has led to this belief is discussed.

3. The sources of gases within the lamp are studied, and the principal gases are found to be water vapor, carbon dioxide, carbon monoxide, hydrogen, nitrogen, and vapors of hydrocarbons.

4. The specific effects produced by these and other gases are determined. It is found that water vapor, which has long been known to be harmful, is the only one that produces perceptible blackening of the bulbs.

5. The blackening by water vapor is due to a cyclic process in which the water oxidizes the tungsten and is itself reduced to *atomic* hydrogen. The tungsten oxide volatilizes and deposits on the bulb, where it is reduced by the atomic hydrogen to metallic tungsten and water vapor is again formed.

6. Attempts to materially improve the life of lamps by the more complete removal of water vapor result in failure. It is therefore concluded that, although water vapor is usually the cause of the short life of poorly exhausted lamps, yet it is not the cause of blackening in well exhausted lamps.

7. The real cause of blackening in well made lamps is proved to be evaporation of the filament, due to its temperature alone.

8. It therefore follows that to improve the efficiency of tungsten lamps, either the rate of evaporation of the filament must be reduced or the evaporated tungsten must be prevented from blackening the bulb.

9. The following methods of improving the tungsten lamp and thus increasing its efficiency, are then discussed in detail:

Introduction of gases, such as nitrogen, mercury vapor, or argon, into the bulb at atmospheric pressure.

Changing the location of the deposit by means of convection currents in gases, so that the bulb opposite the filament does not darken.

10. These methods have met with marked success. The second part of this paper will deal with a particular type of lamp; *i.e.*, a tungsten lamp containing nitrogen at about atmospheric pressure.

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, October 10, 1913.

Copyright 1913. By A.I.E.E.

TUNGSTEN LAMPS OF HIGH EFFICIENCY—II

NITROGEN-FILLED LAMPS

BY IRVING LANGMUIR AND J. A. ORANGE

The first part of this paper outlined principles upon which radical improvements in the efficiency of tungsten lamps may be based.

It was shown that the desired improvement can be obtained by preventing evaporation of the filament or by preventing blackening of the bulb. By the introduction of considerable pressures of such gases as nitrogen, mercury vapor or argon into the lamp the blackening can be practically avoided and the evaporation of the filament reduced very considerably.

By making use of these principles we have been able to construct practical tungsten lamps which, starting at a specific consumption of about 0.40 watt per candle, have run over two thousand hours, the average specific consumption during life being less than 0.5 watt per candle. It should be pointed out at the outset, however, that such a degree of improvement as this has been reached only in lamps taking large currents.

In this second part of the paper we will describe the methods by which these results have been attained.

The early experiments with lamps containing nitrogen at atmospheric pressure were made with ordinary single loop filaments of 0.005 and 0.010 inch diameter placed in long heater lamp bulbs. These lamps were set up on life test at such a voltage that the temperature of the filament was 2850 deg. K.

In order to compare these with ordinary lamps, similar lamps with evacuated bulbs were set up on life test with the filaments at the same temperature.

The nitrogen-filled lamps with the filaments 0.005 inch dia-

meter had a specific consumption of 0.65 watt per candle and had a life of about 90 hours, whereas those with the larger filaments (0.010 inch diameter) had a specific consumption of 0.56 watt per candle and a life of about 300 hours. The bulbs opposite the filaments remained clear, although a slight brown deposit of tungsten nitride collected in the upper part of the bulbs. The candle power of these lamps remained above 80 per cent during their entire life, failure being due in every case to breakage of the filament after this had decreased considerably in diameter.

The vacuum lamps, on the other hand, had a specific consumption of 0.41 watt per candle, but the bulbs blackened rapidly, the candle power falling to 80 per cent in about 40 minutes. Since the filaments of the vacuum lamps burnt out after 2 to 5 hours whereas those of the nitrogen lamps lasted 50 to 100 times as long, it is evident that the rate of evaporation of the tungsten is materially reduced by the presence of the nitrogen.

These results indicated clearly the desirability of using a filament of large diameter. The larger filaments gave not only a better efficiency at any definite temperature, but also a much longer life. Thus doubling the diameter decreased the specific consumption from 0.65 to 0.56 and increased the life from 90 to 300 hours. The improvement in the efficiency, as was pointed out in the first part of this paper, is due to the relatively greater heat loss by convection from small wires. The life of the filament is determined largely by the loss of tungsten from the filament by evaporation and has been found to be dependent on the *relative* decrease in diameter caused by this evaporation. If the rate of evaporation per unit area from large and small wires were the same, the lives of various filaments run at a given temperature would be roughly proportional to their diameters. However, as the evaporation of tungsten in nitrogen is largely a diffusion process, it probably obeys laws similar to those of conduction or convection of heat from a wire; that is, for wires of small diameter, the actual amount of tungsten evaporated would be nearly independent of the size of the wire. The rate of evaporation *per unit area* would thus be approximately inversely proportional to the diameter. The relative lives of very small wires in nitrogen are therefore nearly proportional to the squares of their diameters.

Design of Filament

These results were decidedly encouraging, for both the efficiency and the life of the lamps can be improved by increasing the diameter of the filament.

It is, however, not desirable to use filaments of very large diameter if similar results can be obtained with smaller ones. The current taken by a filament increases approximately with the three-halves power of the diameter. Thus, for wires of the sizes used in the preceding experiments, the currents needed to maintain a temperature of 2850 deg. were approximately:

Diameter		Current
inches	mm.	amps.
0.005	0.127	3.0
0.010	0.254	8.5
0.020	0.508	24.0

Unless very low voltages are used, the power consumed with the larger wires is so great that only very high candle power lamps can be made.

Therefore it was of vital importance to increase the effective diameter of the filament without decreasing its resistance, and various methods of doing this were tried.

This result may, for example, be obtained by using a tubular filament. The method which has thus far proved most satisfactory, however, is to wind the filament into the form of a tightly coiled helix.

The use of a helically wound filament presents several very interesting features. The life of ordinary single loop filaments is limited by the irregularities in diameter which develop after a considerable amount of tungsten has evaporated. These irregularities, after they first appear, tend to magnify themselves very rapidly, on account of the tendency for the current to overheat any spot which becomes thinner than the rest of the filament. The overheating increases the rate of evaporation and rapidly causes failure.

In the gas-filled lamps, however, when helically wound filaments are employed, a new factor is introduced which entirely counteracts this tendency to overheat in spots. In designing the filaments of these lamps, it is evidently desirable to wind the filament on as large a mandrel as possible, in order to obtain the advantage of the large diameter. Since tungsten is a relatively soft material at the operating temperature of these lamps, too large a mandrel should not be used, as otherwise the weight of the filament pulls out the helix very materially in a few

hours, and the heat lost by convection may thus become greater than if a helix of smaller diameter had been used. In actual practise the filament is designed so that the amount of sagging during life will be perceptible, but not enough to cause too great a change in the characteristics of the lamp.

If, during the life of the lamp, any part of the filament should, for any reason, evaporate more rapidly than the rest, so that the filament becomes somewhat thinner, this portion will have less mechanical strength than the rest and will therefore sag more rapidly. The helix will therefore open out wherever the filament becomes thin or becomes overheated. This will cause increased heat loss both by convection and radiation, and thus prevent local overheating or spotting.

The use of helically wound filaments increases the life of the lamp many times beyond the life that would be obtained with a straight filament running at the same efficiency. This is especially true of the smaller sizes of wire.

Besides the helically wound filament, various other forms have been tried, and, for special purposes, many of these have decided advantages.

Design of Bulbs and Location of Filaments

In the ordinary evacuated lamp, the choice of a suitable bulb is a comparatively simple matter. It must be of convenient size and shape, and provide sufficient room for the proper mounting of the filament. Furthermore, it must have as large an inside surface as possible, so that the density of the deposit of evaporated tungsten will be small. It is also desirable to have the bulb at a sufficient distance from the filament and so related to the power input into the lamp that the bulb does not become overheated. This latter is not only desirable from the point of view of safety (in case of lamps for domestic service), but because it is difficult to remove water vapor so thoroughly from the bulbs that the life of the lamps will not be greatly shortened by an overheating of the glass.

In the nitrogen-filled lamps, however, several other factors must be considered, especially in the lamps of high candle power.

In ordinary lamps about 20 per cent of the energy radiated from the filament is intercepted by the glass and causes heating of the bulb. In the nitrogen lamp, beside this radiated heat, there is an additional amount of heat carried to the bulb by convection—an amount varying with the type of lamp and

ranging from 6 to 40 per cent of the total input. The convection currents carrying this relatively large amount of heat travel vertically upwards from the filament and strike a relatively small area of the bulb, which thus tends to become greatly overheated. Unless special precautions are taken, this overheating will cause the liberation of enough water vapor to cause attack of the filament and consequent blackening of the bulb. It is thus highly desirable, in ordinary cases, if small bulbs are to be used, that the filament should be placed in the lower part of the bulb. This has the further advantage that it allows sufficient surface of glass in the upper part for the deposition of the tungsten nitride.

For a similar reason it is generally desirable, although not necessary, to make the bulbs with their height considerably greater than their horizontal diameter.

By special design of the bulb, satisfactory lamps have been made with bulbs of only one-half to one-third as large a volume as that of evacuated lamps of the same wattage. This means that for bulbs of the same volume the nitrogen lamps give roughly from five to ten times the candle power of evacuated lamps. The bulbs of such lamps naturally run much hotter than those of ordinary lamps. The upper parts of the bulbs are often at 100 to 200 deg. cent. or more, while the lower parts are sometimes much cooler than this, although closer to the filament.

Several special varieties of heat-resistant glass have been used for the bulbs, which can thus be made smaller, while it becomes easier to get rid of water vapor. Transparent quartz bulbs have been tried, but do not seem to have sufficient advantage over some of the special glasses to offset their present high cost.

Lead-in Wires and Supports

For some of the larger size lamps which take heavy currents (20-30 amperes) it has been necessary to devise special types of lead-in wires. The ordinary platinum leads have been discarded entirely, even in the smaller sizes. Several types of heavy current leads have been successfully used. Most depend on the use of special alloys which have the same coefficient of expansion as the glass. Bulbs of special glasses into which tungsten or molybdenum wire can be sealed directly, have also been used.

In many of the larger lamps the lead-in wires pass through the lower end of the lamp. In this case they can be made

short. In others, however, the leads are brought in from the top. This requires more care in the construction of the seal if it is exposed to the heat from the convection currents. Screens are sometimes used to protect the seal or other glass parts from direct contact with the convection currents, and to reduce convection.

Various Types of Nitrogen-Filled Lamps

We have seen that at constant temperature, both the efficiency and the life improve as the diameter of the wire is increased. With very large wires (0.020 to 0.040 inch diameter) which take 20-60 amperes, the specific consumption may be as low as 0.40 watt per candle and probably even less, and yet give a life over a thousand hours. It will probably be worth while, in some cases, to use nitrogen in low-current lamps, even if an efficiency no better than that of vacuum lamps is obtained, in order to gain certain other advantages of the nitrogen-filled lamps, such as better color of the light, higher intrinsic brilliancy, etc.

The principal limitation of the new type is therefore that of current. There is no practical upper limit to the current, provided the voltage is not lowered to keep constant power consumption.* With increasing current, larger and larger filaments are used and the specific consumption may be lowered towards the limit of 0.20 watt per candle, which is fixed by the melting-point of tungsten. Unless special expedients are employed, the cooling effect of the leads lowers the efficiency of the lamps by an amount that is inversely proportional to the voltage and nearly independent of the size of the wire or the current strength.

With voltages of 20 volts or more, this effect is not serious, but for voltages as low or lower than 10 volts, it may become very important.

For the particular type of nitrogen-filled lamp which has at present been furthest developed, it may be said that a life of over 1500 hours is obtained at a specific consumption less than 0.50 watt per candle only in large units taking over ten amperes. Lamps running at 0.6 to 0.7 watt per candle have been made in units taking at least 5 amperes.

No serious difficulty has been met in making high-voltage

*As an example, a lamp taking 60 amperes and giving 6600 candle power at 0.40 watt per candle has been successfully run.

lamps. In nitrogen at atmospheric pressure with properly constructed lamps there is no tendency toward arcing, even at 250 volts. Many lamps taking 6 or 7 amperes at 110 volts have been made up and run at 0.6 to 0.7 watt per candle, with a life of over 1000 hours.

A number of special types of nitrogen-filled lamps have been made and tested. Among these the most interesting, for the present, are perhaps the following:

1. *Large Units of Very High Efficiency* (0.4 *to* 0.5 *watt per candle with a life of* 1500 *hours or more*). These take currents of 20 to 30 amperes and (except in units over 4000 candle power) are therefore best run from a-c. circuits by means of small transformers or auto-transformers giving a voltage depending on the size of unit desired. Thus, with 30 volts and 25 amperes, the power would be 750 watts and this, in a lamp at 0.45 watt per candle, would give 1670 candle power. Higher or lower candle power may be obtained by using other voltages. Typical lamps of this kind are shown in Figs. 1 and 2.

2. *Small Units of Low Voltage.* These take currents of ten amperes or less and voltages as low as four or five volts. The specific consumption with 1000-hour life ranges from 0.6 to 1.0, or even 1.25 watt per candle, according to the current used.

These lamps are adapted for series street lighting on 6.6-ampere circuits (at 0.6 to 0.7 watt per candle), for stereopticon lamps, automobile headlights and in general wherever a source of high intrinsic brilliancy, steadiness and white color is needed.

3. *Lamps to Run on Standard Lighting Circuits* (110 *volts*). Large units of this type (several thousand candle power) have a specific consumption of 0.5 watt per candle or less. With smaller units the efficiency is ordinarily not so high.

A lamp of this type is illustrated in Fig. 3. The leads may be brought in from the top, in which case they are preferably made longer so that the filament remains in the lower part of the bulb.

Special Advantages of the Nitrogen-Filled Lamps

Besides its high efficiency, the features of the new lamps which may, at least for certain purposes, prove of advantage, are:

1. *Color of the Light.* The temperature of the filament being 400 to 600 deg. higher than that of ordinary lamps, causes the light to be of a very much whiter color, so that it comes closer to daylight than any other form of artificial illuminant except the d-c. arc and the special Moore tube containing carbon dioxide.

The color is almost exactly like that which can be had for a few minutes by running an ordinary tungsten lamp at double its rated voltage.

Work is at present under way to develop special color screens

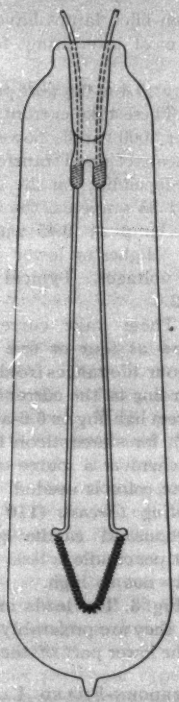


FIG. 1—HIGH EFFICIENCY NITROGEN-FILLED LAMP FOR LOW-VOLTAGE CIRCUIT

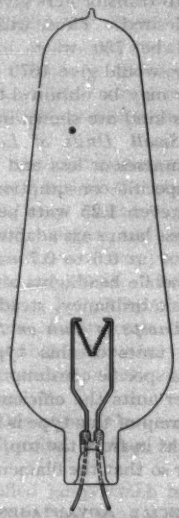


FIG. 2—HIGH EFFICIENCY NITROGEN-FILLED LAMP FOR LOW-VOLTAGE CIRCUIT

which, when used with this light, will give a true daylight color (corresponding to the radiation from a black body at 5000 deg. cent.). From measurements with the spectrophotometer, it can be calculated that the screens which will accomplish this

purpose will absorb from 65 to 75 per cent of the light, so that the net specific consumption will be about 1.5 to 2.0 watts per candle for a pure daylight color. At present, to accomplish this purpose with ordinary tungsten lamps, screens must be used which absorb so much light that the total specific consumption is between 10 and 12 watts per candle.

2. *High Intrinsic Brilliancy of the Filament.* At the operating temperature of the nitrogen-filled lamps the intrinsic brilliancy

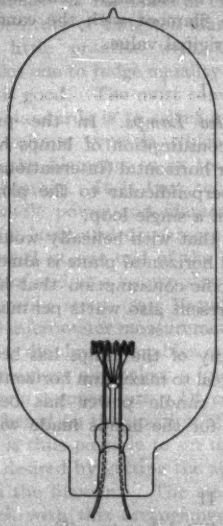


FIG. 3—NITROGEN-FILLED LAMP FOR 110-VOLT CIRCUIT

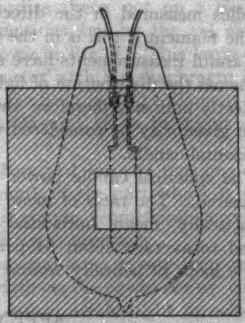


FIG. 4—LAMP AND SCREEN USED FOR CALIBRATION OF BLUE GLASS

of the filament is about 1200 candle power per sq. cm. In ordinary tungsten lamps, on the other hand, running at about 1.25 watts per candle, the filaments have a brilliancy of only about 150 candle power per sq. cm. The brilliancy of the filament of the nitrogen lamp is thus about eight times that of the ordinary lamp.

This feature, combined with the high degree of concentration

preferably used, renders these lamps particularly useful for projection work, such as for headlights or for stereopticons.

3. *Constancy of Characteristics During Life.* It is often possible so to design these lamps that their ampere-,volt-, candle power characteristics remain practically fixed during the greater part of their life. In any case, however, since there is no deposit on the bulb to cut off the light, the candle power practically never falls below 75 per cent (this decrease sometimes being due to sagging). The lamp usually fails by the breakage of the filament with the candle power well above 80 per cent of its original value.

APPENDIX I

Light Distribution of Nitrogen-Filled Lamps. In the preceding paper, wherever the specific consumption of lamps has been given, it is expressed in watts per horizontal (international) candles measured in the direction perpendicular to the plane of the filament if this is in the form of a single loop.

Careful measurements have shown that with helically wound filaments the distribution of light in a horizontal plane is almost perfectly uniform, therefore the specific consumption that has been given may be considered to represent also watts per mean horizontal candle.

The spherical candle power of many of the lamps has been measured. The ratio of mean spherical to maximum horizontal (practically mean horizontal also) candle power has been found to average about 84 per cent for the lamps made with single loops of helically wound wire.

APPENDIX II

Method of Photometry for Nitrogen-Filled Lamps. The usual practise in dealing with incandescent lamps is to determine volts, amperes and candle power either at a predetermined value of one of these quantities or else at a predetermined efficiency by the "cut and try" method. In the case of a lamp which presents so many variables as does the nitrogen-filled lamp, however, it is more systematic to regard temperature as the fundamental variable.

The method that has been adopted for these lamps is not essentially novel, although it does not appear to be as well known as it deserves to be.

First: The temperature has been defined by the equation

$$T = \frac{11{,}230}{7.029 - \log H}$$

where T is the absolute temperature and H is the intrinsic brilliancy of the filament in international candle power per sq. cm. (projected area).*

Second: A most useful criterion in practise for equality of temperature of tungsten filament is that of color-match.

A little practise with the Lummer-Brodhun photometer enables one to judge equality within about 5 deg. if the illumination is good. The most convenient way of setting up temperature standards is to select a number of well-seasoned lamps of high-voltage type in which the anchors are tightly pinched onto the filaments so as to prevent variable cooling effects at the contact. It is best to standardize these, not on a basis of candle power and filament dimensions, but by the aid of a special lamp and diaphragm as shown in Fig. 4. This lamp is arranged at one end of the photometer with the diaphragm in front of and at a known short distance from it. The filament is preferably stout (say 10-mil or 0.025-cm.) so as to admit of good micrometer measurements.

The diaphragm enables one to disregard the end portions of the filament and select a known length of the part which is at uniform temperature. Of course a simple geometrical correction based on the position of the screen is necessary.

It is thus possible to set up the special lamp at any temperature desired by getting the appropriate candle power per sq. cm. from the filament. The standard lamps are brought to color-match with this arrangement and in this way a set of lamps with known relation between voltage and effective temperature is obtained. The life of the ordinary standard lamps would be very short indeed if they were run at the same temperature as nitrogen-filled lamps. For this work, therefore, the standards cannot be used directly as color-standards. For this reason a most important accessory is introduced in the form of a set of special blue glasses. It is not easy to get a blue screen which will perfectly facilitate color-match of tungsten filaments at dif-

*(The derivation of this formula together with a description of other methods of obtaining the temperature of filaments will soon be published, probably in the *Physical Review*.)

ferent temperatures, but a special blue glass has finally been obtained which answers exceedingly well.

Four distinct screens of different intensity are used, each carefully finished as a uniform plate, and any or all of these may be combined with a tungsten filament run at any temperature and the result will color-match correctly against another tungsten filament at a higher temperature.

It may be shown theoretically and experiment confirms that the following relation holds:

If T is the temperature of a filament which is viewed through screens A, B, C, etc.,

T_1 is the temperature of a filament which matches the above.

Then $\frac{1}{T} - \frac{1}{T_1} = a + b + c$ etc.

where a, b, c etc. are constants for the screens A, B, C, etc. Thus one only needs to maintain one standard temperature by means of standard lamps and that temperature can be so low that great permanence is insured.

The constants for the four glasses once determined, there are available a number of standard temperatures ranging from 2250 deg. to 3600 deg. K.

By the use of these screens it is an easy matter to set a lamp up at a voltage such that the filament has a standard temperature, say 2850 deg. To do this it is simply necessary to adjust the voltage so that the color of the light from the lamp is the same as that which comes from the standard lamp when viewed through one of the special blue screens.

Since the efficiency in vacuum is very simply related to the color of the light, this method of photometry gives a very simple and direct way of knowing the exact effect which the nitrogen has on the efficiency of the lamp.

DISCUSSION ON "TUNGSTEN LAMPS OF HIGH EFFICIENCY—I AND II" (LANGMUIR AND ORANGE), NEW YORK, N. Y., OCTOBER 10, 1913.

John B. Taylor: I would first like to make a few remarks, to give the audience a few moments' time in which their eyes may become accustomed to the great difference in brilliancy between the filaments they have just been looking at and the enlarged projected image, which, perhaps, will have a brilliancy of something in the order of one-millionth part of the brilliancy of the lamps at which you have been looking.

I can testify to the satisfaction that this lamp gives in projection work after using the lamp with a projecting microscope and also for photomicrographic work, particularly color photography. The steadiness of the lamp as compared with an arc lamp, either hand-fed or automatic, leaves the worker absolutely free to give all his attention to the subject or specimen and the photographic plate. A switch turns on the lamp and the light source is always exactly in the same position. Its intensity will always be the same, and repeated exposures will give similar results. The color value is good, as it is almost as white as a carbon arc. In projection work half of the light is thrown backward, but a large portion of this can be conserved by the use of a reflecting mirror, properly placed so that the reflected image practically coincides with the source of light. The projection arrangement I have here will show this. This reflector arrangement is of no value in the case of the carbon arc, as the electrode casts a shadow backwards. As shown in Fig. 1, the reflected image is inverted with respect to the direct image.

FIG. 1

(Mr. Taylor then threw the projection on the screen.)

I ask Dr. Langmuir if he can tell us anything of the ratio of the resistances of the filament hot and cold in the nitrogen-filled lamps. This may be an important factor when the lamp is switched on if there is a momentary overload of fifteen or twenty times normal.

John W. Howell: Dr. Langmuir has made an analysis of the residual gases in tungsten lamps, and has devised an apparatus for the making of qualitative analyses in determining the five constituents in one cu. mm. of gas. That is a marvelous achievement. During all the years we have been working on incandescent lamps we have been interested in residual gases, we have known they were there, and we had a general idea what they must be, but we never had the initiative to try to measure them in quality and quantity as Dr. Langmuir has done.

The first summary of Dr. Langmuir's, on page 1932, reads* as follows: "The efficiency at which tungsten lamps may be profitably run, is limited principally by the blackening of the bulb." Dr. Langmuir should have drawn that statement more carefully, so that it would refer to large lamps. It is true of large lamps, but it is not true of the small lamp. Forty-watt lamps and all smaller standard lamps blacken so little that they break before the blackening becomes objectionable and their useful life is their total life. These lamps constitute over 75 per cent of all lamps sold. In large lamps the efficiency is limited by the blackening of the bulb. There are two reasons for this. The small lamps have thin filaments. If these filaments waste away by evaporation, and one spot is hotter than the other, the hottest spot will waste fastest, and it will break there. This wasting will break a thin filament in shorter time than a thick filament, consequently the thin filaments break before the evaporation has proceeded far enough to blacken the bulb. We test in the laboratory all 40-watt lamps at 0.9 watts per candle. Their total life at 0.9 watt per candle is about 400 hr., and at the end of that time they are not blackened sufficiently to render them objectionable or make us take them down. Large-diameter lamps will live longer. Another reason why lamps with thick filaments blacken more than those with thin filaments is that thick filaments are used for high candle power lamps and in these lamps, for practical reasons, the bulb area is not nearly so large relative to the candle power or filament surface as in thinner filament lamps, and as the evaporation from a filament is proportional to its surface, these larger lamps with less bulb surface per unit of filament surface would get blacker in a given time. This difference in bulb surface in relation to filament surface is very great and causes large lamps to become useless by blackening before the filaments break.

As to the second paragraph in Dr. Langmuir's summary, I have recognized for some time that there are three different kinds of blackening in a tungsten lamp, and that the ordinary blackening which proceeds very slowly and is uniform throughout the bulb is caused by the evaporation of the filament. I believe that same thing of carbon lamps, and if you will refer to the TRANSACTIONS of this Institute for March, 1894, you will find a paper written by Prof. Anthony on "Incandescent Lamps Containing Heavy Gases." Prof. Anthony concludes with the statement that the blackening of the carbon lamp is caused by the evaporation of the filament, and Prof. Elihu Thomson, and Prof. Robb, of Hartford, and Mr. Doane agreed, in discussing the paper, that the blackening was due to this cause.

In discussing that paper I said that there were two kinds of blackening, one was due to evaporation, I believed, and the other was not. Now, the other kind of blackening, which I thought was not due to evaporation, is always irregular in its deposition on the bulb. In carbon incandescent lamps we fre-

*As first printed, previous to presentation.

quently met an irregular blackening which we call mottling, and mottling always occurs in a lamp which has a defective vacuum. Of course, there are different kinds of defective vacua, but only a few kinds of defective vacua that produce that mottling. There is one condition which always produced a mottled discoloration of the carbon lamp, and that was in the case of lamps which we made at one time, in which we put a little clay in the anchor clamp to hold the filament. These lamps were always discolored irregularly and with mottling. That same mottled discoloration is found in tungsten lamps. This lamp (exhibiting lamp) illustrates a mottled lamp, but the discoloration is not black.

It is a lightish discoloration, caused by oxygen, by air. That is a mottled discoloration. I believe that any residual gas in a lamp which attacks the filament will produce a mottled discoloration.

The other kind of blackening in lamps is due to water vapor. We have believed for a good many years that the gas which comes from the glass of the lamp as it is heated was water vapor, but we did not know it. Dr. Langmuir proves it and now we know it. It is impossible, I think, to exhaust out of a lamp with a mercury pump all of the water vapor which comes off the glass when you heat it. The only way in which we can take it out is by the use of phosphoric anhydrid.

Water vapor in a carbon filament lamp does not cause the lamp to blacken as in a tungsten filament lamp. Here are two tungsten lamps (exhibiting lamps) that were made in the spring of 1907. When we made these lamps we exhausted them together in the same way. After they were exhausted and sealed up as finished lamps, I took one lamp and with a gas torch heated the bulb hotter than it had been heated in exhaustion, and then the two lamps were put up on a life test and burned over night, and the result of one night's burning was that the lamp that had been heated to drive the water vapor off the bulb into the lamp was black the next morning and the other one remained perfectly clear. We discovered also that when we heated the bulb during exhaustion the water vapor was sufficiently removed so it did not come out any more afterward.

Away back, about 1890, there was a lamp put on the market called the novak lamp, a carbon lamp with one mm. of bromine in it. The lamp was not commercially successful because the bromine had, as nitrogen has, bad effects and good effects, but in that carbon lamp the bad effects were greater than the good effects, and the result was a disadvantage and the lamp did not live.

At that time I made a lot of experiments on the effects of gases in lamps. I made measurements with four gases, nitrogen, hydrogen, bromine and chlorine. The lamps I used were first exhausted with a very good vacuum, and then increasing amounts of each one of these gases, separately, were admitted to the lamp, and the change made in the specific consumption of the lamp

by the cooling effect of the gas was noted, and these changes were plotted in a curve which showed the effects of any amount of either one of these four gases in the lamp. At first it was impossible to make a lamp which would burn well with any gas in it. It was only when we realized the absolute necessity of dryness in the gas that we succeeded, but when we got these gases absolutely dry, neither one of them had any ill effects on the lamp. I mean as to making it black; but they all cooled the filament and this cooling effect is what we measured.

The effect of water vapor in a carbon lamp is to render the filament sooty and black. This makes it a very excellent radiator of heat, so that it is cooled by radiation to such a degree that the candle power falls away down, and yet the bulb remains clear.

Farley Osgood: The question that interests the operating engineer is, what is the hope of the development of this lamp in small units? As Mr. Howell has said, 75 per cent of the lamps used are in small units.

J. E. Randall: You have had here an exhibition of this new development and a demonstration of the operation of these lamps during a period of a few moments. I presume that I am the last person in this hall to have seen any lamps of this kind operated in the Research Laboratory at Schenectady. I saw some lamps there today and identified them as those that I saw operating under the same conditions a number of weeks ago. They have been operating continuously since the first time I saw them. Therefore, I think we can say that this development is successful. The development will be beneficial because it marks a long step in the energy efficiency of a device that is notoriously inefficient.

If we grade the quality of lamps by the initial efficiency, that is, filament temperature at which they will show a certain performance, the so-called nitrogen lamp will take a very high rank. If we establish as a standard of performance, the initial efficiency at which a lamp will develop 90 per cent of its theoretical candle hours during one thousand hours of burning, candle maintenance and mortality both considered; and if, on this basis, we call the raw carbon filament lamp 100, the various types will rank as follows:

Raw carbon filament lamp	100
Treated carbon filament lamp	119
Gem filament lamp	149
Tantalum filament lamp	206
Tungsten filament lamp	359
I have not complete data for the new lamp but it surely would have a rating of	600

We should not consider these developments as extending the lives of lamps. Their success should rather be gaged by their energy saving. The real advantage of any improvement in the incandescent lamp is utilized by raising efficiency rather than by prolonging life.

The way for the new lamp was to a great extent prepared by the production of ductile tungsten. Methods of shaping the drawn tungsten wire into helical coils have been so developed that they are of signal assistance. Accuracy of control of wire diameter, which, one may say, has almost reached perfection, will doubtless add speed to the commercial development of this latest lamp.

William McClellan: I ask whether Dr. Langmuir in closing will say a word about frequency in connection with the lamps, especially low frequencies, with low-voltage lamps. Is there any difference between that and the ordinary tungsten lamp?

Irving Langmuir: Different frequencies of alternating current?

William McClellan: Yes. The point is that the ordinary carbon lamp at 25 cycles, low wattage, does not flicker so that it can be noticed. When you come to the tungsten lamp it flickers considerably. I am interested in knowing whether the new type of lamp will be different from the tungsten, or practically the same.

John W. Lieb, Jr.: The question naturally arises, what is going to be the effect of this great movement forward in lamp efficiency on central station service, and what is its effect going to be on the general question of improvements of efficiency and life of incandescent lamps? Undoubtedly these new lamps will necessitate a revision of our criteria which have prevailed hitherto as to what should be considered as the useful life of the lamp. Useful life, as we know, has been established in accordance with general agreement that when the lamp has depreciated in candle power to 80 per cent of its initial value the useful life of the lamp has ended; it has reached the "smashing point." Now, with these new developments in the lamp, and the increased efficiencies which have been attained, it will be necessary for us to modify our figure, or at least give it new consideration in the light of the electrical data which these new lamps present. The central stations have long ago passed that period when they could afford to exhibit any fear as to the ultimate result of an improvement in the art, in any direction in which the art might progress. This new development will help to reach that consummation which we have all been hoping for, that the electric light will reach the humblest home and be as easily accessible to the humblest of our citizens as kerosene.

Another question which is raised by these lamps is, what will become of the arc lamp? I think it is no empty prediction that the arc lamp under the impulse which this new development produces, will achieve further advances to put itself in line to continue the contention with its new competitor.

M. G. Lloyd: We are told that the nitrogen is at about one atmosphere pressure. I ask the reason for using that particular value. I should like to know whether it is considered objectionable to have a higher pressure than one atmosphere inside the bulb.

H. M. Fales: Telephone companies are interested in the success of the tungsten lamp for street lighting purposes. The present carbon arc lamps produce variations in the lighting circuit of such frequencies that serious disturbances are often caused inductively in telephone circuits located on the same street. With tungsten lamps this is not the case. The disappearance of inductive disturbances in telephone circuits has already, in a number of cases, been traced to the substitution of tungsten lamps for arc lamps.

Farley Osgood: I might suggest that Dr. Langmuir in closing say a word about the stability of these lamps. Our friend Mr. Lieb has indicated the possibilities of it for arc use, which is very interesting to operating engineers.

Irving Langmuir: The difference in brilliancy, pointed out by Mr. Taylor, between the inner and outer portions of the helix as thrown on the screen, is due, I think, principally to reflected light from the inner sides of the turns. In other words, the conditions in the interior of the helix more nearly approach those in a so-called "black body" furnace. The difference in temperature between the inner and outer part of the wire may be approximated by calculation, and is found to be less than 10 degrees, an amount too small to account for the large difference in brilliancy.

It might at first sight appear that the imprisonment of light by reflection back and forth between the adjacent turns of a helix causes a waste of light energy. In a sense, this is true, but since the heat energy is also imprisoned to nearly the same degree, the power needed to heat the filament is decreased in about the same ratio as the light. The efficiency at any given temperature is therefore not seriously affected by the helical winding. Experiments confirm this.

Mr. Howell's criticism that the failure of small lamps is due principally to breakage and not to blackening is, I feel, quite correct. In writing the paper I had in mind lamps of 40-watt size, or larger. Although under the usual operating conditions the failure of 40-watt lamps running at normal efficiency is, as Mr. Howell points out, rarely due to blackening, yet our experiments have shown clearly that as soon as the specific consumption of such lamps is lowered to about 0.8 watts per candle, the bulbs blacken relatively rapidly and the candle power often falls to 50 per cent of the initial candle power, or lower, before failure occurs.

I did not mean to claim in the paper that we were the first to find that water vapor in lamps is injurious, or to suggest evaporation as a cause of blackening. I know that the presence of water vapor has been considered extremely harmful, in both carbon and in tungsten lamps, from the early days of their manufacture. I have pointed out that evaporation as a cause of blackening was one of the theories often applied to the blackening of lamps.

I feel, however, that evaporation was considered as a *possible explanation*, rather than as the *known cause* of blackening in well made lamps.

It has been my experience that the men in lamp factories always endeavored to explain every particularly good or "freak" lamp by assuming that the vacuum in the lamp had been better than usual, thereby directly inferring that the presence of residual gases limited the life of ordinary lamps.

Many of the German lamp factories have carried on very careful scientific investigations as to the cause of blackening of tungsten lamps, but so far as I know, have not found evaporation to be the cause.

The prevalent theory among these investigators seems to be that the blackening is primarily due to electrical disintegration. This theory has sometimes been discarded in favor of the evaporation theory, because the rate of blackening apparently did not perceptibly depend on the voltage of the lamp, but did rise rapidly with the temperature of the filament, according to a curve resembling a vapor pressure curve. These were Prof. Anthony's main reasons for concluding that evaporation was the cause of blackening. Investigations during the past ten years, however, have shown that the electrical discharge (thermionic current) from a hot wire in vacuum is independent of the voltage and does rise with the temperature, according to just such a curve as that observed for the rate of blackening. Thus both of the main reasons which had led Prof. Anthony to conclude that evaporation was the cause of blackening fall to the ground.

On the other hand, the objections to the electrical theory which have previously seemed most serious, disappear.

The real reason for our conclusion that evaporation and thermionic currents are not related, is based on actual measurements of these thermionic currents, which are being published elsewhere (*Phys. Review*, Dec., 1913).

What Mr. Howell has said about the uniformity of the deposits caused by evaporation is in accord with our experience. The blackening due to water vapor, however, is not always, or even usually, irregularly deposited, although in some cases it may be so to a marked degree. In some cases we have observed that blackening by water vapor is limited to the hottest portions of the bulb. In fact, if heat is applied locally to a part of the bulb, this alone may blacken. Sometimes blackening in presence of gas is influenced by electrical discharges. But it is more usual even in presence of water vapor, to obtain very uniform deposits, which in appearance cannot be distinguished from those due to normal evaporation.

I may have conveyed a false impression in the paragraph on the effect of argon. That paragraph refers only to argon at very low pressures. Argon at high pressures is just as good, if not better than, nitrogen. The results so far indicate that argon will probably be substituted for nitrogen in the lamps as

soon as it becomes readily available. The gas is very hard to make on a small scale, but on a large scale it can be made very cheaply, comparatively speaking.

In regard to the flicker of these lamps when used on alternating current, I may say that this depends entirely on the size of filament used; in other words, on the current taken by the lamp. With lamps taking 6.6 amperes on 25-cycle current, the flicker is just barely noticeable. With lamps taking larger currents, it cannot be detected by the eye.

The pressure of gas used in the lamps is preferably as high as is consistent with safety. In order to avoid all possibility of explosions, we aim to employ such an amount of gas that the pressure will be about atmospheric pressure during the normal operation of the lamp. The gain in efficiency which could be obtained by using higher pressures is entirely negligible.

The stability of the lamps is as good as that of ordinary lamps. Of all the lamps shipped from Schenectady to New York for this meeting, not one was broken.

In conclusion, I should like to say that I consider the real credit for this work is due to Dr. W. R. Whitney, who, by the encouragement he has given and the wonderful spirit of coöperation he has created in the laboratory, has made the result possible.

A paper presented at the 287th Meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1913.

Copyright 1913. By A.I.E.E.

INDUSTRIAL SUBSTATIONS

BY H. P. LIVERSIDGE

The growth of the demand for electrical energy during the last two decades has been one of the very significant indications of the increasing prosperity of the country at large. Remarkable growth is noted in the demand for electrical energy for all uses, but particularly in the demand for energy for industrial purposes. This latter demand has created certain problems which have necessitated the development of new methods by which energy is delivered to consumers.

It is the purpose of this paper, after tracing very briefly the engineering development of this branch of the central station industry, to give some discussion of the salient features of the design and installation of electrical plant equipment in consumers' premises, which we shall designate as "industrial substations." Certain specific installations will be cited and certain conclusions drawn.

The growth of the supply of electrical energy, by central stations to consumers, for industrial purposes, dates back to the commercial introduction of the electric motor. Starting with the early installations of a few horse power each, the development has been such that at the present time industrial consumers are found with individual installations totalling several thousand kilowatts capacity.

In the early days the industrial consumer was supplied like other consumers, from the regular service mains of the central station. The service was either d-c. or a-c. according to the character of the central station mains. Energy was supplied without the necessity of installing transforming or switching

equipment in the consumer's premises, other than the usual service switches controlling the incoming lines.

It was early seen by operating companies that, due to the increased demand, the method by which energy is brought to the consumer and there distributed would have to undergo marked changes, and that it would be necessary to devise means by which the large blocks of energy demanded could be satisfactorily supplied by the central station. The changes necessary to accomplish these results have affected particularly: (a) the size and location of the transforming apparatus, (b) the character of the equipment required to control these increased capacity installations, and (c) the voltage at which the energy is delivered to the consumer.

Coupled to the greater demand of the industrial consumer supplied from high-voltage alternating-current lines was, oftentimes, the need for direct-current service. This added requirement necessitated the installation of rotating apparatus for transformation from alternating current to direct current, besides the static transformer equipment usually provided.

These larger and more complicated installations practically made necessary the location of the transforming apparatus in the consumer's premises. In addition, many of the larger services made advisable the supply of energy at a higher potential than that of the regular distribution circuits of the central station system, particularly so when the distance of transmission was comparatively long.

The installation of high-voltage services supplying static transformers or rotating transforming apparatus, or both, necessitated an electrical equipment comparable to that installed in central station substations. Moreover, the same care is given to the design and construction. This is clearly evidenced in the industrial substations later cited as examples in this paper.

The present discussion will deal more particularly with large industrial substation installations located in comparatively built-up manufacturing districts, and supplied from high-voltage alternating-current lines. At the outset, consideration must be given to the factors that determine the decision on the part of the operating company whether or not to install a substation in consumers' premises.

In general, when the load does not exceed a few hundred kilowatts and the consumer's demand is for alternating current entirely, it is very usual practise to supply the consumer through

an installation of transformers fed directly from the distribution lines of the operating company. In such cases, no substation is necessary in the consumer's premises.

On the other hand, when the amount of energy demanded requires a heavy capacity transforming equipment, or when the requirements of the consumer are such that a combination service of both direct current and alternating current must be supplied, then it becomes necessary to install protective apparatus and switching equipment of a more elaborate nature than in the former case; and the industrial substation is therefore designed.

The problem of electrical design of industrial substations presents usually no great difficulties. The equipment necessary to meet the requirements of each consumer will be found to have been more or less standardized by the operating company, with such modifications in particular instances as are necessary.

The variations between designs are due in general to differences in the capacities of the installations, the equipment installed, the conditions of service, and the voltages at which the substations are supplied.

The problem of *physical* design very often presents many more difficulties, particularly the disposition of the electrical equipment in the space available. The four factors of: (1) space economy, (2) operating requirements, (3) fire hazard and safety to attendants, and (4) cost, govern in most cases the physical layout.

Not infrequently a decided limitation is imposed on the physical arrangement by the very cramped quarters allotted to the substation equipment by the consumer. On the other hand, the erection of new industrial buildings usually allows space sufficient for proper design of the substation. In the matter of the design of industrial buildings, much room exists at the present time for closer co-operation between the consumer and the central station's engineers, to the consumer's own great advantage.

Contrasts are evidenced both in the electrical and physical designs of industrial substations in different localities in this country, but are no more marked than in the designs of generating stations and substations. It is proposed later herein to cite examples of industrial substations in operation in different parts of the country, and to give descriptions of certain ones which are taken as typical.

For purposes of further analysis, the electrical design of an industrial substation briefly may be divided into the following components: (a) the incoming feeders; (b) the arrangement of the busbars if any are installed, and the switching equipment; (c) the transforming equipment; and, finally, (d) the distribution system of the consumer. This latter is very often left to the consumer himself, and usually is given little attention by the central station engineers.

Detailed discussion of the various components which make up the electrical equipment of an industrial substation as noted above, need not be taken up at this point, but rather consideration will be given to them as they are instanced in the following examples of typical installations, at present in operation in this country.

Plant No. 1

Silk Manufacturing Plant Supplied by Two Industrial Substations Located on Premises. Static transformer equipment only is installed, totalling 1720 kw. in the two substations. The load is of very constant nature, and the service is twenty-four hours a day, seven days a week throughout the year. No regular attendant is required, but general maintenance is provided by consumer's electricians.

The description will be limited to the more recent one of the two substations, which is a fireproof building, 10 ft. (3.04 m.) wide by 30 ft. (9.14 m.) long by 10 ft. 6 in. (3.19 m.) high at lowest point, of brick with concrete; one side adjoins a factory building. Ample provision is made for lighting and ventilation by window openings (fire-resisting glass) and by natural-draft ventilators in the roof.

The substation is supplied at 2400 volts, two-phase, 60 cycles, by two feeders, both entering the building underground from overhead lines. Lightning arrester protection is provided by electrolytic lightning arresters connected to the overhead lines and located in enclosures at the base of the terminal poles.

The present transformer equipment consists of two banks of oil-insulated self-cooled power transformers of 400 kw. capacity each, and one bank of lighting transformers of 60 kw. capacity; making a total of 860 kw. capacity in this substation.

The high-tension switchboard consists of four panels, controlling two incoming feeders and two transformer banks. Connections are as shown in Fig. 1 under "Transformer House No. 2." Automatic hand-operated oilbreak switches are connected in each 2400-volt circuit as shown in the diagram.

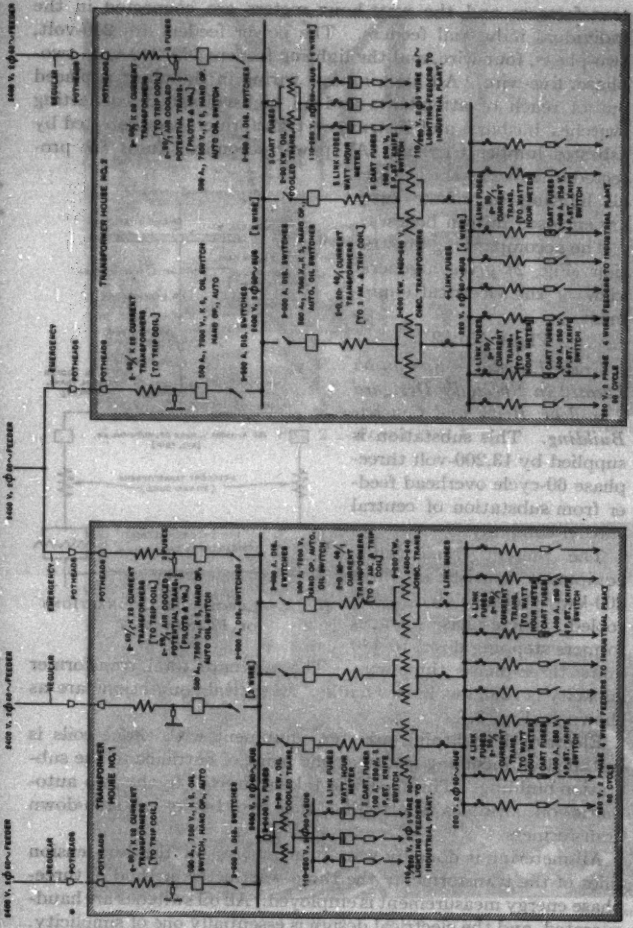


Fig. 1—Electrical Connections of Plant No. 1

All metering is done on the low-tension side of the step-down transformers and the watt-hour meters are connected in the individual industrial feeders. The power feeders are 240-volt, two-phase, four-wire, and the lighting feeders 120/240-volt, two-phase, five-wire. All high-voltage wiring in the plant is placed out of reach of attendants and all high-voltage disconnecting switches, busbars, and instrument transformers are protected by asbestos lumber barriers. All power secondary fuses are protected by asbestos shields, and all lighting secondary fuses are enclosed in iron boxes.

The accompanying illustration (Fig. 2) gives a general view of the electrical equipment.

Plant No. 2

Grain Elevator. Substation Located in Specially Designed Two-floor Brick and Concrete Building. This substation is supplied by 13,200-volt three-phase 60-cycle overhead feeder from substation of central station company.

The present transforming equipment consists of three 200-kw. oil-insulated self-cooled single-phase transformers stepping down to 440 volts three-phase three-wire. The ultimate total transformer capacity is 1200 kw. in two banks. Electrical connections are as shown in Fig. 3.

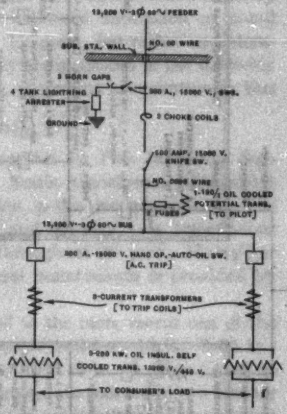


FIG. 3—ELECTRICAL CONNECTIONS OF PLANT NO. 2

Electrolytic lightning arrester equipment with choke coils is installed on incoming feeder at the point of entrance to the substation building. This feeder is taken directly to the two automatic oil switches controlling the two banks of step-down transformers.

All metering is done by watt-hour meters on the low-tension sides of the transformers; the three-wattmeter method of three-phase energy measurement is employed. All oil switches are hand-operated, and the electrical design is essentially one of simplicity.

Provision is made for the safety of the operator by the erection

FIG. 2.—PLANT NO. 1 [LIVERSIDGE]

FIG. 4.—PLANT NO. 3 [LIVERSIDGE]

of asbestos lumber barriers, etc., enclosing all accessible high-voltage conductors and parts.

The character of the load is irregular.

Plant No. 3

Ship and Engine Building Plant. Synchronous Converter Substation Located in Consumer's Power House. The substation equipment consists of four 300-kw., 60-cycle synchronous converters, having a total capacity of 1200 kw. and supplying direct-current energy to consumer at 250 volts, two-wire. The substation is arranged for parallel operation, if desired, with two engine-driven direct-current generators of the consumer. The substation is supplied by two 6000-volt, two-phase, 60-cycle

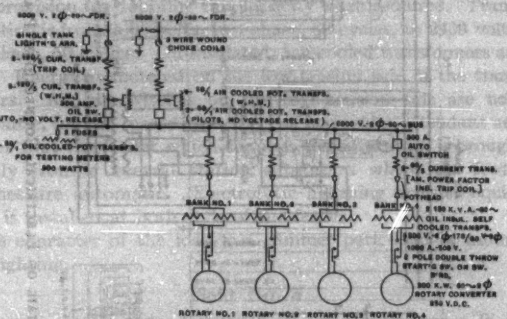
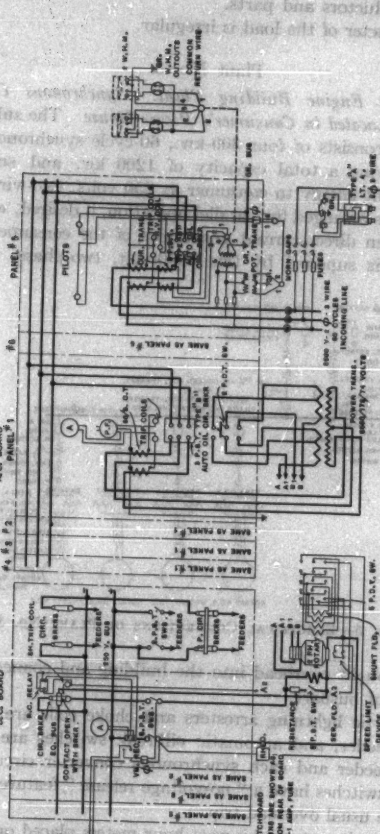


FIG. 5—ELECTRICAL CONNECTIONS OF PLANT NO. 3

feeders brought overhead into the building and connected to a single set of busbars.

Electrolytic lightning arresters and choke coils are installed on each feeder, and automatic oilbreak switches are provided for each feeder and each synchronous converter circuit. The feeder oil switches have a "no-voltage release" feature in addition to the usual overload trip.

All energy is metered by watt-hour meters placed on the two incoming feeders. All high-tension switching equipment and the alternating-current switchboard, busbars and lightning arresters are located on a gallery along one side of the building. The oil-insulated self-cooled transformers for the synchronous converters are located underneath the gallery.


D.C. BOARD
A.C. BOARD
PANEL #1
PANEL #2
PANEL #3
PANEL #4
PILOTS
TELEPHONE
BATTERY
D.C. RELAY
CHG. SHUNT
EQ. BUS
IN-TRIP COIL
CHG.
SERIES
CONTACT DISC
WITH SHUNT
FEEDER
FEEDER
FEEDER
FEEDER
150 V. BUS
BANK AS PANEL #1
BANK AS PANEL #2
BANK AS PANEL #3
BANK AS PANEL #4
BANK AS PANEL #5
BANK AS PANEL #6
NOTE: SWITCHBOARD
DIAGRAM IS SHOWN AS
VIEWED FROM REAR
OIL BUS
AUTO OIL CIR. BRKR
TRANSFORMER
OIL CIR. BRKR
OIL CIR. BRKR
POWER FUSES
2000/115V VOLTS
INCOMING LINE
60 CYCLES
2000 V. 3-Ø
3 WIRE
FUSES
SHUNT FLD.
SERIES FLD.
SHUNT FLD.
SERIES FLD.
SHUNT FLD.
SERIES FLD.

A general view of the plant is given in Fig. 4 and single-line diagram of connections in Fig. 5. Detail connections for the electrical equipment are shown in Fig. 6. Interest attaches to the sheet metal hoods placed over the transformer banks and used for purposes of fire protection and ventilation.

The conditions of service are twenty-four hours, six days a week. Attendance is by the regular operating force employed by the consumer.

Plant No. 4

Static Transformer Substation (Fig. 7) Supplying Amusement Park on Outskirts of Metropolitan District. The equipment is located in a small brick substation building on the park grounds, and consists of 400 kw. transformer capacity at present time, with provision for doubling this capacity when required. Transformation is from 6000 volts, two-phase, 60-cycles, to 2400 volts, two-phase, 60-cycles. Oil-insulated, self-cooled transformers are used. Energy is metered on the low-tension side of the transformers. All oil switches on the high-tension side are non-automatic, for the reason that there is no regular attendant and further that the feeder which supplies the substation is brought directly from a central station substation where the feeder switches are automatic. Electrolytic lightning arrester equipment is installed at both ends of the feeder.

The character of the load is a summer park load of motors and lighting.

Plant No. 5

Synchronous Converter Substation in Car Manufacturing Plant. This is supplied at 13,200 volts, three-phase, 60-cycles, by two underground feeders from a central station substation.

The initial equipment consists of two 300-kw., six-phase, 250-volt, direct-current compound wound synchronous converters with necessary banks of single-phase oil-insulated self-cooled "step-down" transformers. The ultimate converter capacity is 1600 kw. in four units. A single set of high-tension busbars is provided, and the entire high-tension switching equipment is electrically remote-controlled. Also, a high-voltage service is taken off the busbars to additional transformers for fire pump motor. Watt-hour meters are connected on the 13,200-volt incoming feeders.

A specially designed two-story substation building houses all the apparatus. The building is entirely inside the walls of the

industrial plant, but is separated from it by suitable fire-proof walls. The static transformers and high-voltage equipment are located on the second floor; the synchronous converters, the direct-current switchboard and the remote control board for the high-voltage oil-break switches are placed on the first floor.

The plant operates in parallel with an existing direct-current steam-driven plant.

An interesting point in connection with the consumer's distribution system is the provision for electrical remote control of the 250-volt direct-current supply switches which are located in various parts of the manufacturing plant. These separate services are tapped to heavy capacity feeders, arranged in a ring system, and the service switches are controlled from the industrial substation.

The character of service at this plant is ten hours per day, six days per week, and the attendance is supplied by the consumer.

Fig. 8 shows elevation of the substation and illustrates the general arrangement of the electrical equipment.

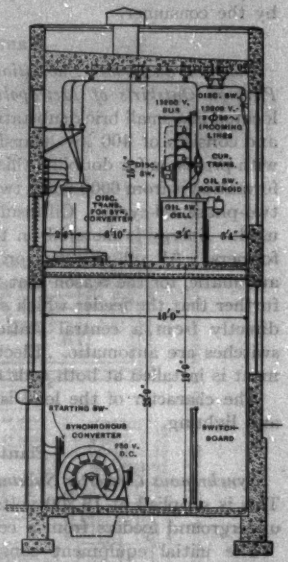


FIG. 8—SECTIONAL VIEW OF PLANT NO. 5

Plant No. 6

Static Transformer Industrial Substation of Paper Manufacturing Plant. Current is supplied at 6600 volts three-phase by two incoming feeders, one of them brought directly from generating station and the other from a substation.

The transforming equipment consists of six 150-kw., 6600/440-volt, single-phase power transformers, arranged in two banks of three transformers each, giving a total connected capacity of 900 kw.

The feeders are taken through automatic oil-break switches to a single set of busbars connected to a line containing current

FIG. 7.—PLANT NO. 4 [LIVERSIDGE]

FIG. 9a.—PLANT NO. 6 [LIVERSIDGE]

FIG. 9*b*.—PLANT NO. 6 [LIVERSIDGE]

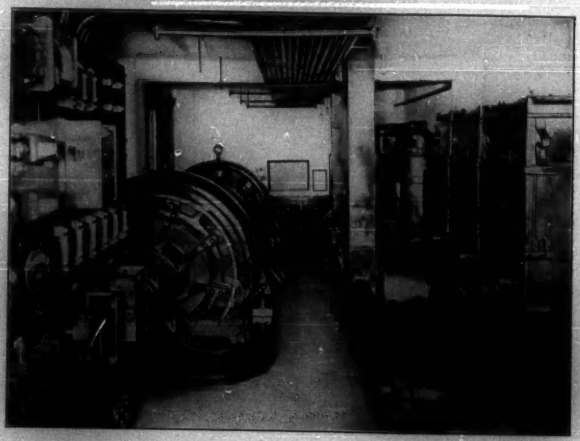


FIG. 9*c*.—PLANT NO. 7 [LIVERSIDGE]

transformers used in connection with totalizing instruments and meters. This line extends to another bus from which is tapped, through automatic oil-break switches, the circuits which supply the two step-down transformer banks. All metering is

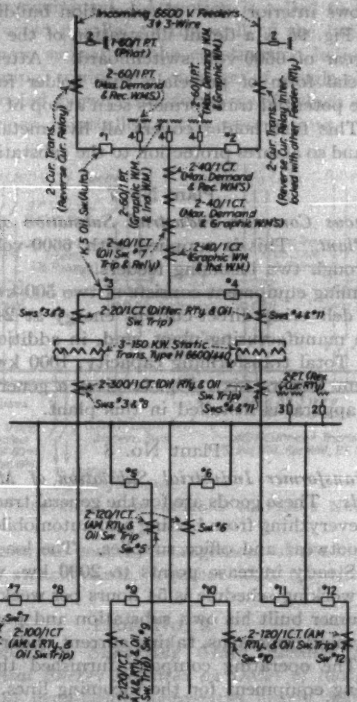


FIG. 9—ELECTRICAL CONNECTIONS OF PLANT NO. 6

done at 6600 volts three-phase, as indicated above, and the two-wattmeter method of three-phase energy measurement is employed.

The consumer's load is supplied at 440 volts three-phase taken from the low-tension side of the power transformers.

The arrangement of both high-tension and low-tension connections in the substation offers many points of interest, and, in particular, the grouping of the six 440-volt, three-phase feeders is to be noted.

Fig. 9 gives single-line diagram of substation connections, Fig. 9*a* shows interior view of substation building and equipment, and Fig. 9*b* is a detail illustration of the apparatus and wiring at rear of 6600-volt switchboard. Attention is called to the special form of porcelain fuse holder for high-voltage fuses on the potential transformers seen at top of switchboard in Fig. 9*a*. This fuse holder covers all live metal parts of the fuse clips, and so assures protection to the substation attendants.

Plant No. 7

Synchronous Converter Industrial Substation of Type Manufacturing Plant. This is supplied with 6600-volt, three-phase current through two incoming feeders.

Transforming equipment consists of two 500-kw. synchronous converters delivering direct-current energy at 240 volts three-wire to the manufacturing plant, and, in addition, two 90-kw. balancers. Total transforming capacity, 1000 kw. Number of direct-current feeders, six. Fig. 9*c* gives a general view of the substation apparatus installed in this plant.

Plant No. 8

Static Transformer Industrial Substation of Manufacturer of Rubber Goods. These goods are for the general trade, and include practically everything from belting and automobile tires down to the finest footwear and office supplies. The load at present is 1000 kw. Steady increase points to 2000 kw. within another year. The working schedule is 54 hours per week.

The consumer built his own substation and purchased all of the transforming apparatus, taking current under a high-tension contract. The operating company furnished the switch cells and switching equipment for the incoming lines, and also provided suitable metering apparatus, but, further than this, has no connection with the consumer's substation.

Energy is supplied by two 13,200-volt, 60-cycle, three-phase feeders brought to a single set of busbars through automatic oil-break switches (see Fig. 10). An electrolytic lightning arrester equipment is connected to the busbars through disconnecting switches. Potential transformers and totalizing

current transformers are connected in the busbars and operate totalizing instruments and watt-hour meters, the two-wattmeter method being employed.

Fig. 11 gives a sectional view of the high-tension switch and busbar structure, and indicates the location of the aluminum cell lightning arrester equipment. Attention is called to the single concrete wall erected parallel to the wall of the building and furnishing the main support of the construction indicated.

The transforming equipment consists of single-phase, oil-insulated, self-cooled power transformers, of which one bank of three transformers is installed at the present time.

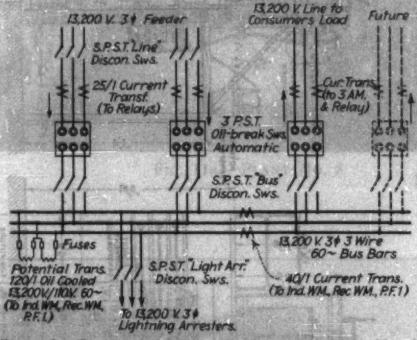


FIG. 10—ELECTRICAL CONNECTIONS TO PLANT NO. 8

Fig. 11*a* shows the general arrangement of the high-tension and low-tension switchboards, together with the transforming apparatus.

Plant No. 9

Industrial Substation Supplying Grain Elevator Equipment and Other Electrical Energy Required on Docks of Railroad Company. The total installation aggregates nearly 3000 kw., of which approximately 600 kw. is maintained exclusively for fire pumping purposes. In general, the equipment is for the operation of the grain elevator apparatus used in loading and unloading cars and for general lighting around the docks.

So far, the operating company has not had a demand in excess of 500 kw., and the hours of service are entirely dependent upon the hours of arrivals and departures of vessels and trains. The

railroad company provided the substation building and operates the station exactly as though it was an isolated plant.

The substation is supplied by three 6900-volt, three-phase incoming feeders, two of which constitute a loop into and out of the station. The loop may be closed or broken independently

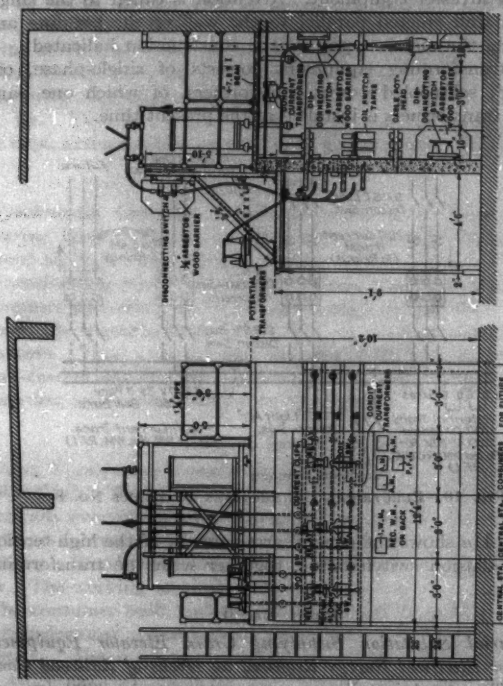


FIG. 11—CONSTRUCTION DETAILS OF HIGH-TENSION STRUCTURE, PLANT NO. 8

of the consumer's busbar by an oil-break switch connected ahead of the line-disconnecting switches of the two feeders.

Three-phase, oil-insulated, self-cooled transformers are used in this station for power service, and single-phase, oil-insulated, self-cooled transformers for lighting. Fig. 11*b* shows the exterior of the substation building, and Fig. 11*c* gives a general view of the interior.

FIG. 11*a*.—PLANT NO. 8 [LIVERSIDGE]

FIG. 11*b*.—PLANT NO. 9 [LIVERSIDGE]

FIG. 11c.—PLANT NO. 9 [LIVERSIDGE]

FIG. 12.—PLANT NO. 10 [LIVERSIDGE]

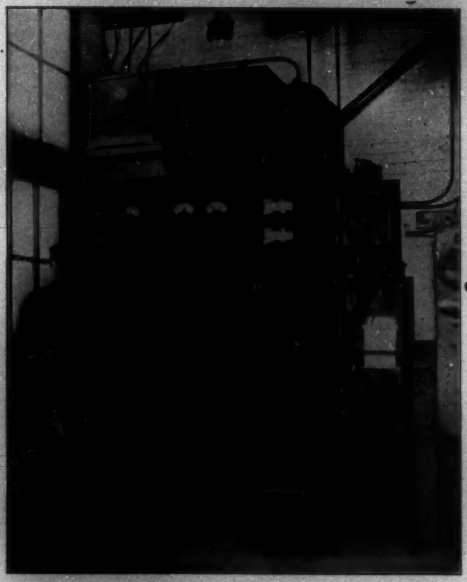


FIG. 13.—PLANT NO. 11 [LIVERSIDGE]

FIG. 14.—PLANT NO. 12 [LIVERSIDGE]

Plant No. 10

Industrial Substation Comprising Vehicle-Charging Equipment in a City Garage. The equipment consists of one three-unit motor-generator set and three-panel control board, as shown in Fig. 12. The motor-generator set consists of one 145-kw., 120-volt, and one 45-kw., 80-volt compound-wound direct-current generator, direct-connected to a 285-h.p., 4150-volt, three-phase, 60-cycle, 900 rev. per min. synchronous motor, with a 5-kw., 125-volt, direct-connected exciter.

The switchboard equipment of the substation includes an automatic regulator used in connection with the synchronous motor and employed in order to maintain constant line potential.

The substation is supplied by a 4150-volt, three-phase, 60-cycle incoming line, feeding directly to the synchronous motor through the necessary automatic oil-break switches and starting compensators.

In order to prevent the charging set taking energy from the truck batteries, should the alternating-current supply be interrupted, the generators are equipped with reverse current relays, set to operate the direct-current circuit breakers on four per cent reverse current.

Plant No. 11

Industrial Substation for Cold Storage Plant. The equipment consists of a three-unit motor-generator set embodying one 90-kw., 250-volt and one 25-kw., 250-volt shunt-wound, direct-current generator, direct-connected to a 210-kv-a., three-phase, 60-cycle, 4150-volt synchronous motor with a 5-kw., 125-volt exciter mounted directly on the end of the shaft.

The substation is supplied by one 4150-volt incoming feeder on which are installed electrolytic lightning arresters and choke coils. The feeder is taken directly to the synchronous motor through the necessary automatic oil-break switches and a three-phase starting compensator for the motor. The motor is equipped with an automatic voltage regulator in order to insure constant line potential.

In this installation it has been deemed advisable to protect the direct-current generator circuits by fuses only, instead of by the usual automatic overload circuit breakers.

The attendance at the plant is good and, while the voltage regulator has given some trouble, the operation of the plant is satisfactory. The load for this class of refrigerating service is very constant throughout the twenty-four hours.

Fig. 13 shows the switchboard at this plant, and one end of the motor-generator set, and indicates the extreme simplicity of the electrical equipment installed.

Plant No. 12

Combination of Synchronous Motor Pumping Station and Small Synchronous Converter Substation: Shown in Fig. 14.

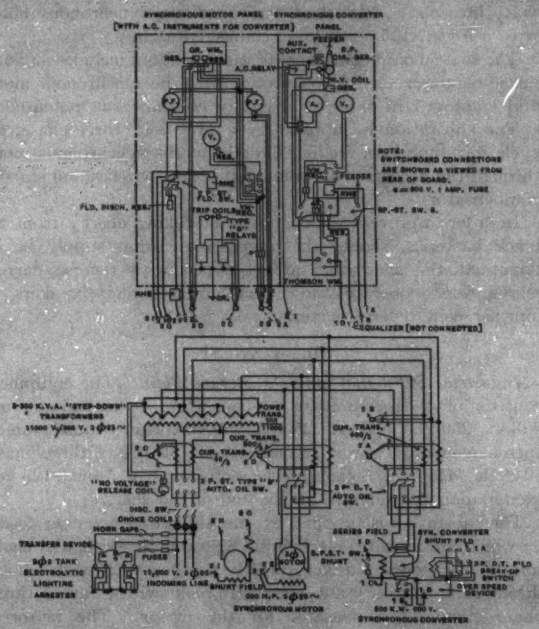


FIG. 15—DETAIL ELECTRICAL CONNECTIONS FOR PLANT NO. 12

This equipment consists of a 600-h.p. pump motor (6,000,000-gallon high-efficiency pump) and a 200-kw. 600-volt railway synchronous converter which feeds a suburban trolley line. The total capacity is approximately 700 kw. Current is supplied at 11,000 volts, three-phase, 25-cycles, on one incoming feeder entering the substation overhead. The feeder is taken

through an oil-break switch, equipped with no-voltage release, directly to a bank of three single-phase step-down transformers which on the low-tension side (368 volts) supply *both* the 600-h.p., three-phase motor and the 200-kw., three-phase synchronous converter.

Both motor and converter are alternating-current starting, from reduced voltage taps on the transformers. A spare transformer unit is maintained in readiness for emergency service. Under agreement between the operating company and the consumer, the operation of the synchronous converter is attended to by the consumer.

The accompanying diagram, Fig. 15, gives the detail connections of the substation equipment.

* * * *

In the descriptions of industrial substations given above, attention has been called particularly to the more important characteristics of design and general construction. At this point it will be interesting to undertake further analysis of those details which have a direct bearing upon the factors to which attention has already been called in the early part of the paper.

These factors may be enumerated again: (1) Space economy; (2) Operating requirements; (3) Fire hazard and safety to attendants; and (4) Cost.

1. *Space Economy.* In all instances this factor should be given careful consideration. Especially is this true when the equipment is to be installed in an already existing factory building, where the consumer has allotted all the space available, and this space permits no latitude in the arrangement of equipment.

Plant No. 3, a synchronous converter substation of four 300-kw. units, is a striking example of the economy which has been effected in this particular. The space provided for the equipment was one corner of an existing engine room which already contained several engine-driven generators, a heavy-duty air compressor, and other miscellaneous power plant auxiliaries. The floor area allotted to the substation equipment measures approximately 30 ft. by 30 ft. (9.14 by 9.14 m.). The height of the engine room permitted the construction of a short gallery upon which was placed all high-tension switching and protective apparatus. This arrangement, while it might not have been selected had a new substation building been erected, neverthe-

less made possible the installation of all apparatus without necessitating any changes in the building construction.

Again, Plant No. 1, which is a static transformer substation, illustrates very clearly the great economies of space to be effected by proper arrangement of the switching and transforming equipment, without impairing, in any way, the efficiency of the design.

Plant No. 10 is also an illustration of an exceedingly compact arrangement of electrical apparatus. In this installation a 285-h.p. motor-generator set and the control switchboard are placed close to the wall of the building. No additional housing was provided in this instance, thereby securing a limited floor area for the installation.

2. *Operating Requirements.* The conditions under which the various equipments of substations operate are often radically different, due to the requirements of the consumer. Careful consideration should be given this point.

One of the important features relating directly to this question is the duration of continuous service, which may vary from a few hours per day to a practically continuous supply. As due provision must be made for inspection and repairs, it is quite evident that, in the case of continuous operation, attention must be given to the proper sectionalization of the apparatus and duplication of equipment. This is indicated in the design of Plant No. 1, Fig. 1. In this case, each individual circuit controlling the incoming feeders and transformer banks is provided with disconnecting switches.

As previously noted, this plant operates almost continuously, and such an arrangement permits of a ready examination of the operating equipment during light loads, without necessitating the interruption of the consumer's service. This type of construction further permits a comparatively simple installation, and obviates the necessity of a duplicate set of busbars and oil-break switch equipment.

In contradistinction to this lay-out, Plant No. 2, Fig. 3, supplying a very intermittent service, is arranged without any means for sectionalization. Provision is made only for disconnecting the single incoming high-voltage feeder from the substation equipment.

Another point to be considered in connection with this question is the operating attention which will be given the installation, either by the consumer or the central station company.

In most cases, however, it is the desire of the consumer to supervise the operation of his equipment, and as a rule this plan is productive of satisfactory results.

It is evident, therefore, that any complications in switching equipment and control apparatus should be studiously avoided.

3. *Fire Hazard and Safety to Attendants.* In connection with this feature, it is interesting to note the tendency toward particular care in construction details as they relate directly to this subject.

Where substation apparatus is to be installed in existing industrial plants, a considerable amount of reconstruction is sometimes advisable. In many cases, the floors and ceilings of the industrial buildings are wood. These should be made fireproof. The usual building alterations consist of the changing to concrete flooring and metal-lined or asbestos-covered ceilings.

In oil-cooled transformer installations, special arrangements are necessary for properly draining the contained oil from the transformer cases. This is accomplished either by pipes connected directly to the transformers or by concrete drains built in the transformer foundations and connected to a common outlet.

An interesting example of this latter type of construction is noted in Plant No. 5, Fig. 8. In this installation, the transformer banks are placed on a concrete base so constructed as to provide a very effectual drainage system for the entire equipment.

The enclosing of high-voltage switchboard equipment to secure the *maximum* of safety to attendants is plainly evidenced in the plant designs to which attention has been called. Asbestos lumber doors and partitions form the more important part of this detail in construction. Besides serving as a protection from accidental contact with high-voltage circuits, these partitions in many cases are excellent barriers for protection from fire.

Plants No. 1, Fig. 2, No. 3, Fig. 4, and No. 8, Fig. 11, may be cited as typifying this feature of construction. A particularly interesting example may be noted in Plant No. 1, Fig. 2, where the high-voltage equipment is entirely enclosed and cannot be reached except by the opening of the several doors composing the enclosing partitions.

4. *Cost.* Not infrequently the central station engineer is limited to a certain minimum expenditure imposed by the prospective consumer, and which in most cases affects the electrical equipment under consideration. It is evident that this limitation may

affect materially the character of the installation; and particularly will this be evidenced in the switchboard and controlling equipment. The changes in this part of the construction are most apparent in the details of control equipment, namely, the type of switchboard, whether marble, slate or open iron frame; the number and type of instruments on the individual circuits, and the character of busbar construction.

These details in many cases are closely related to, and influenced by, the factors already noted.

Nevertheless, there are many points in the design, as above mentioned, that will be directly influenced by the question of construction cost.

Conclusion. In the present paper, all detailed references to costs, and to the economic questions involved in the subject of industrial substations, have been purposely omitted. Furthermore, in the discussion of the plants presented the writer has refrained from all criticism which relates to the question of efficiency in station design.

The attempt has been made, rather, to emphasize how well the engineering design and installation of substations located in consumers' premises, and receiving electrical energy from a central station system, meet the most varied and exacting requirements of the industrial consumer.

* * *

The writer wishes to take this opportunity to express his appreciation of the courtesies shown by the engineering departments of the Commonwealth Edison Company, the Edison Electric Illuminating Company of Boston, the Edison Electric Illuminating Company of Brooklyn, the Rochester Railway & Light Company, and the Philadelphia Electric Company; also to acknowledge the able assistance of Mr. Charles Penrose and Mr. H. C. Albrecht, both of the engineering department of the Philadelphia Electric Company, in the compilation of the paper.

DISCUSSION ON "INDUSTRIAL SUBSTATIONS" (LIVERSIDGE), PHILADELPHIA, PA., OCTOBER 13, 1913.

W. C. L. Elgin: I think Mr. Liversidge has covered many of the important points in relation to substation design, but I have gained the impression that he has paid too much attention to the question of space economy. Although the size of the apparatus readily lends itself in that direction, I think there are many bad designs because too much attention has been paid to obtaining the smallest possible space for the apparatus.

I know of three substations designed for 2000 kw. each; and in examining them, I was impressed with the fact that the principal and only question considered, was apparently to find a place for each piece of apparatus and then to build a wall around it. These substations were only about 20 feet square; and after installing the apparatus there was no room for making repairs. In order properly to inspect any part of the plant that might become defective, it was necessary to go outside of the building, and look into the substation through a window. For this reason, these substations had to be abandoned.

I think the pictures showed that where there was rotating apparatus, reasonable space was allowed, but that the space was smaller where merely static apparatus was installed. In the static substation of 4000 kw. the entire apparatus was installed in a space 30 feet by 10 feet. That space, of course, was ridiculously small. In the next two or three years, I think you will find that this substation will have to be enlarged or otherwise altered.

The cost of the building is relatively small in comparison with the importance of the reliability of service and also with the total cost of the service. The real estate and building costs are practically small items.

One other point in the paper is that of enclosing all the apparatus, especially the high-tension apparatus. I think it should not be enclosed completely, but that partitions, some of which may be made of glass, should be placed around it; or an open space should be provided, of a size sufficiently large to permit of an examination of the apparatus, but small enough to prevent the operator inserting his hands, and making accidental contact. Another advantage of this is that you can locate any trouble in the particular compartment in which it occurs; but if completely enclosed, the smoke will travel from one place to another.

There was another point of which Mr. Liversidge did not speak, and that is the danger, in these cases, from water. It seems to me that substation apparatus should be so designed that it would operate even if completely immersed in water. There has always been a great objection to having water around an electrical installation. I know of a case where a 2400-kw. substation was partially submerged for twenty-four hours and

continued in operation during this entire time. That is an accomplished fact; and we now know that we can operate under these conditions.

I wish to make a plea for more space in substations, instead of space economy.

P. M. Lincoln: Mr. Chairman, I have not much to offer, but I wish to commend the careful thought given in Mr. Liversidge's paper to this question of substations and their design. There has been a great deal of thought given in the past to power stations, but substations and the use of the power therein have been more or less neglected. The substations of the past have partaken somewhat of the nature of "Topsy"—they just grew. I think we are to be congratulated in having someone like Mr. Liversidge, who has given careful attention to this subject, give us the results of his study in a carefully prepared paper such as this.

Mr. Liversidge said the three-wattmeter method was used in some stations and the two-wattmeter in others. Why is that?

What is the method for measuring the maximum demands? Has the maximum demand method of charging come into general use?

Those are some of the questions which occur to me at this time in connection with Mr. Liversidge's paper.

John Mathews: I have noticed that in many of the cases which Mr. Liversidge cited, they use single-phase transformers rather than the polyphase units. The cost of the polyphase is less than the cost of the single-phase unit and the space occupied may be less.

Were there any other features which made the decision in favor of the single-phase unit?

G. W. Brooks: I note in Mr. Liversidge's paper that in the majority of cases installations include two banks of transformers, one of these being spare. It would seem that this is a greater expense than necessary, as reliable service can be secured by the installation of four single-phase transformers, one transformer to be held as spare. This saves the cost of two complete transformers.

In metering power when service is given through two incoming feeders, is it not practical to install current transformers in each of the two incoming lines and connect these transformers in multiple to the same watt-hour meter?

Is it considered desirable to install overload relays on each incoming line feeder where reverse energy relays are used and protection is secured by overload relays on oil switches serving apparatus connected to substation bus?

W. C. L. Eglin: Thinking over some of the remarks I made earlier this afternoon I thought I might possibly have given the impression that I was criticising that portion of Mr. Liversidge's paper regarding space economy. What I wanted to say when I made my statements, was that the apparatus lends itself to

space reduction so well, that that feature is generally abused and the space cut down very much below reasonable limits.

P. V. Stephens: This paper is one of great interest to designing engineers, and there is one point not strongly emphasized in comparison with these other points which have been enumerated. That is, that in addition to the space and the general design, etc., the controlling idea in the design of the substation, especially the industrial substation, should be the continuity of the service that is to be supplied. In other words, in larger installations you will find that this is of prime importance, and it is one of the reasons why a great many of the companies prefer to have their own power and pay more for it, than to run the risk of being shut down because they are depending on one or two feeders.

If you will present to them a lay-out which will guarantee a continuity of service you will go a long way toward getting them to use central station service. One way is to have as many sources of supply as possible. Have at least two feeders from the company's power station to the users, and a two-bus substation system has many advantages. By providing two-way switches on the feeders you can switch on to either bus. This gives a flexible arrangement and greatly decreases the possibility of a shut-down, thereby providing a continuity of service which is a very important factor in supplying power to industrial plants and especially very large plants.

For instance, in the case of a ship-repair plant where a great ship is on the dock to be repaired, and there are heavy overhead and docking expenses all the time the ship is in dry-dock (and to this expense must be added the loss of business), a condition often necessitating a day-and-night job, you can readily imagine what the cost must be in the case of unnecessary delay on an important ship where the steamship company is deprived of its service. You cannot then afford to have a shut-down; and it was on such a proposition in Brooklyn, New York, where I had to design an electrical installation of that kind, that it was necessary for us to give them a positive guaranty of no shut-down on their extensive equipment, and for the last six years they have run continuously without losing a day or night on an equipment of 3500 h.p. in electric motors. But they would have had trouble on four different occasions due to carelessness or accidents, if I had not had the two-feeder, two-bus system in operation.

Charles Penrose: In further extension of the remarks of the previous speaker I ask Mr. Liversidge whether in the design of such substations use cannot be made of bus-sectionalizing switches on single-bus systems in order to insure continuity of service, rather than the necessity of a *double-bus* system such as has been suggested by the immediately preceding questioner? For these reasons: the double-bus lay-out incurs double initial expense, which is undesirable from the point of view of investment, re-

quires increased upkeep and adds to the complexity of operation. The latter is one of the important points which Mr. Liversidge has tried to bring out in his paper this afternoon, namely, the desirability of freedom from those complexities which may spell "trouble" in the operation of the substation.

In regard to the particular interest which Mr. Liversidge's paper has had, at least for me, I would say that it was my good fortune in connection with Mr. Albrecht to be asked by Mr. Liversidge to assist in a small way in the preparation of the paper, and that it has occurred to me more than once what great wealth of material for a paper is offered at this time by the industrial substations already in service in this country. Mr. Liversidge, because of the limitation of space and time, had to restrict his remarks to some 12 stations, which are in operation in different American cities.

The possibilities that are open for further investigation of industrial substations throughout the country are almost limitless, even if consideration is given only to the larger installations. The engineering characteristics of industrial substations have reached the point where the proper design of these plants is comparable to the design which enters into the installation of large central station substations.

But Mr. Liversidge has drawn clearly the line of demarcation between what apparatus should be installed in industrial substations, and what apparatus may not be permitted because of lack of space and complexity of arrangement.

A contrast of the 12 substations which were discussed shows many points of difference in the voltages, phase and frequencies of the sources of supply. The several plants included static, synchronous converter, or a combination of both kinds of equipment. All of these points could only be dwelt upon fully in a very long paper.

The point I want to bring out is that the subject is one of very great importance due to the tremendous development we now have in electrical installations in consumers' premises, where, as I have already said, you may have a substation whose equipment is comparable in many cases to that of the largest substations in those of the larger central station systems.

Harold Goodwin, Jr.: The previous speakers have laid emphasis on the question of continuity of service, particularly with regard to emergency services. Yet I should not like this discussion to go down as unqualified endorsement of emergency services. It may be necessary in some cases, but in other cases the expense might not be warranted. Even if the central station puts it in, the consumer has to pay for it in the end, and this militates against low rates.

The necessity for emergency service depends largely on the value of continuity of service. No one has been able to evaluate this, but the ratio of cost of current to total operating expenses has bee n found a fair indicator of it. It would be interesting if this

ratio could be added to the data on each plant mentioned in the paper.

H. P. Liversidge: In reply to the points brought out by Mr. Eglin relating particularly to the subject of space economy, I would say that I thoroughly agree with him in the matter of greater space for substation lay-outs. The point that is desired to be emphasized is rather that the space allotment is usually a minimum, due primarily to the fact that the question is often decided before the engineer is asked to consider the installation of the equipment. In most cases this space is too small to be at first considered, and only after considerable effort on the part of the operating company is enough space given to permit of a satisfactory installation. It is quite evident, therefore, that such a condition usually results in a lay-out occupying the extreme minimum of building space.

Replying to Mr. Lincoln's question concerning the two-wattmeter or three-wattmeter method of measurement, I might say that while the two-wattmeter method is perfectly correct, there are practical considerations which arise in operating conditions where the three-wattmeter method is to be preferred.

Referring to the installation of spare transformer units, I would say that, under certain operating conditions one additional transformer will be sufficient for replacing any of the regular operating transformers in case of repairs, etc. Where an interruption of service due to transformer breakdown would be serious, however, it would seem better practise to install a complete duplicate installation of transformer units and switch board equipment.

The subject of continuity of service is one that is of interest to all. The question of duplication of switch and busbar equipment to insure greater reliability of operation, however, under certain conditions is doubtful. For normal capacities, modern switchboard construction has reached that state of development where the danger of breakdown in the busbar or switching equipment need not be seriously considered. It would seem, therefore, that the best installation is that which embodies simplicity in its arrangement rather than the duplication of equipment to insure continuity of operation, in the event of switchboard failures. Where continuous operation is necessary, proper installation of section switches in the busbar and busbar taps will obviate the necessity of complete duplication of buses and switch gear and will permit of a ready examination of the operating equipment.

A paper presented at the 287th meeting of the American Institute of Electrical Engineers, Philadelphia, Pa., October 13, 1913.

Copyright 1913 by A. I. E. E.

RELATION OF PLANT SIZE TO POWER COST

BY P. M. LINCOLN

That a large plant can supply a given power service as a part of a general power supply business more economically than a plant of only sufficient size for that given service, is so manifest that most engineers are ready to admit it without argument. However, every isolated plant that is installed where central station service is available is, to a certain extent, evidence that there is somebody not yet convinced of this general truth; consequently a discussion showing why this general statement is true may not be out of place.

There are three distinct reasons why a large plant can take care of a given service more economically than a small one. These reasons are:

1. Because the first cost per kilowatt of the large units entering into the construction of a large plant is lower than of the small units entering into the construction of a small plant, thereby reducing the first cost of the apparatus necessary for the given service and, therefore, reducing the annual fixed charges thereon.

2. Because a large plant inherently can be operated more economically than a small one, and because, further, the large plant can afford to introduce economies which would be out of the question in a small one.

3. Because of the existence of diversity factor, whereby one kilowatt of capacity in a central station will serve a combined load that would take considerably more than one kilowatt if each part of that combined load were to be served separately.

Further discussions of these three reasons will be taken up in the order named above.

1. Relation of Size and First Cost

A large plant will cost less per kilowatt than a small one. This is simply a specific statement of a general law. The larger the amount involved, the cheaper each unit becomes, no matter what the commodity may be: Kilowatts come cheaper when purchased a thousand in one machine than when bought singly; just as cigars come cheaper by the box, or freight rates are lower by the car load.

Although this law is usually recognized qualitatively, few engineers have an adequate conception of how much it means quantitatively. To give some idea of the extent to which this reduction in cost occurs, a number of curves are given herein showing approximately how much the size affects the cost per kilowatt of some of the types of apparatus that enter into the

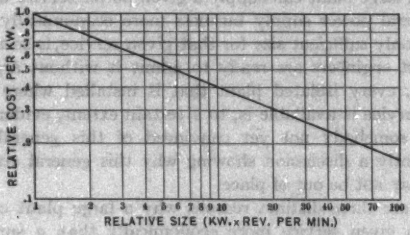


Fig. 1

make-up of a power station. In giving these data, logarithmic cross-section paper is used for two reasons; first, because the range of the data covered in a given curve may be thereby increased, and second, because the law connecting size and cost per kilowatt usually takes an exponential form, thereby enabling us to represent the relation by a straight line on this kind of paper.

Fig. 1 gives data of this nature upon electric generating apparatus. In apparatus of this kind, a variation in size is almost invariably accompanied by a simultaneous variation in speed, and both speed and size have an important influence upon the cost per kilowatt. It is quite possible, however, to take cognizance of the speed variation as well as the output variation and to derive a law that couples the cost per kilowatt with both output and speed. The data given in Fig. 1 are the result of

the inspection of a considerable number of electric generator costs. This curve shows the relative variation of cost per kilowatt as it depends upon size and speed of generator units. An inspection of the curve will show, for instance, that if the speed

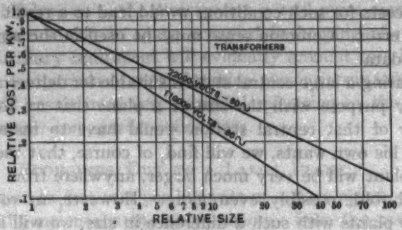


FIG. 2

remains constant the cost per kilowatt will decrease by approximately 65 per cent for an increase of ten fold in the size of the unit.

In Fig. 2 similar data are given for some typical lines of transformers.

In Fig. 3 data are given upon the relative costs of different sizes of boilers.

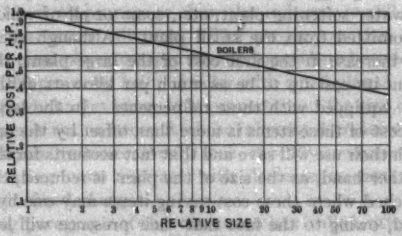


FIG. 3

In using any of these curves it must be borne in mind that a curve is simply a method of stating a general law and that no such general law can take cognizance of an unusual condition. For instance, if we tried to extend the curve for 110,000-volt transformers so as to obtain the cost of a one-kw. transformer, the result would be absurd. When an engineer has designed the

smallest possible transformer suitable for use on 110,000 volts he will necessarily have a transformer of a capacity very much in excess of one kilowatt. In other words, it is impossible to design a transformer of so high a voltage and so low an output. As a consequence, therefore, the use of these curves to obtain relative costs for such conditions would lead to a result which is sadly in error. Common sense must be used in the application of these data.

Comparing a large central station suitable for delivering power for every purpose with the size of a plant that an individual customer of that central station would have to install, if he supplied his own wants, we will find, of course, that the central station plant will be very much larger, anywhere from ten to a thousand fold, possibly even more. However, in comparing complete plants with such a difference in size, we will find that we do not realize the whole of the difference in cost that would be indicated by comparing difference in the cost of the individual parts. The reason for this is that the large plant is inherently more elaborate than the small one. A large plant will naturally be equipped with such items as mechanical stokers, coal and ash handling machinery, coal bunkers and storage yards, superheaters, economizers, condensers with all their auxiliaries, double sets of busbars, distant control electrically operated switches, heat-insulating lagging on all boilers and steam pipes, feed water heaters, water softening plant, etc., some or all of which items may be omitted from the small plant. Although such items cause an increase in the first cost of the large plant, they still do not run its cost up to be as much per kilowatt as the small plant not equipped with these refinements. In the large plant the first cost of these items is more than offset by the operating cost which their use will save and that fact accounts for their use. On the other hand, as the size of the plant is reduced, the point is approached where these cost-saving items may one by one be eliminated, owing to the fact that their presence will lead to a greater resultant cost of power than their absence. It is only where power is produced in relatively large quantities that these various cost-saving devices will pay. This matter will be treated further under the next heading in this paper.

Another saving which would be effected by concentrating power-producing apparatus at a single point instead of distributing it throughout the premises of the various customers served is the tremendous aggregate saving in space. As the size of the

units increases, the saving in space occupied becomes marked. For instance, a 10,000-kw. turbo-generator does not take up anything like ten times as much space as a 1000-kw. generator. In fact the space occupied is but little more than for a 1000-kw. unit, and when we compare the space occupied by a 10,000-kw. unit with a 100-kw. unit, the discrepancy is still more marked.

The aggregate saving in space occupied in housing of plant and in the auxiliary equipment will evidently amount to a large item and the comparison of central station power versus individual plants will result in a very material reduction in the first cost of the former compared to the latter.

2. Economies Due to a Large Plant

The reduction in first cost per kilowatt of a large plant over a small one is by no means the only economy from the concentration of a large amount of power generating apparatus at one point. In fact the reduction in first cost is only a small part of the total saving that can be obtained by such a move.

The total cost of power may be divided into two parts; viz. first annual fixed charges (interest, depreciation, taxes and insurance), that depend upon the first cost and second, operating costs (fuel, labor, repairs, supplies, and superintendence) that are almost entirely independent of the first cost. We have just seen that size has a considerable influence on the first of these divisions and now we propose to show this influence is still more marked on the second division. The proportion that fixed charges enter total power costs is usually somewhere between 30 per cent and 60 per cent, being smaller with small plants. The reason that fixed charges increase in proportion as the size of the plant decreases is not on account of the inherent decrease of this item (because, as we have already seen, it really increases) but because operating costs increase with decrease in size much faster than do fixed charges.

A preceding paragraph of this discussion has called attention to the fact that the larger the plant, the greater refinements it can afford to install. The first matter that requires attention as the size increases is usually the matter of fuel saving. In large plants the cost of fuel usually amounts to somewhere between 50 per cent and 75 per cent of the total operating expense. Obviously, therefore, the fuel bill offers by far the best target when one goes hunting for economy. In plants of small output the fuel bill bears a smaller proportion to the total, not

at all because of better economy but because the other expenses, such as labor, superintendence, etc., go down slower than does fuel as the plant size decreases.

The condenser is undoubtedly the most important piece of apparatus so far as fuel economy is concerned. A large plant is almost invariably placed where suitable condensing water can be obtained, whereas a plant for serving the individual customer has to go on that customer's premises and even if the expense of a condenser is warranted, in a great many cases suitable condensing water is not available except at a cost which makes its use prohibitive. The inherent fuel economy of condensing units as compared with non-condensing units is nearly in the ratio of two to one and it can, therefore, be seen at once how large a factor the condenser becomes in the matter of economical operation.

As the plant increases in size we soon come to a point where an investment in superheaters and economizers will begin to pay. The economy effected by these devices in a large plant is of the order of about 10 per cent of the fuel. When our fuel bill is of the order of 50 per cent of the total cost of power, it is evident such a saving will justify a very considerable expenditure. As the plant output grows smaller, however, the fuel bill becomes a constantly decreasing proportion of the total cost and at the same time the relative cost of superheater and economizers increases, so that we soon arrive at a point where their installation will no longer pay. It is only the plant of comparatively large output that can afford to use this economy.

Uniformity in fuel supply is another item which is of very considerable importance, as is realized by those who have been obliged to change the quality of fuel fired from time to time. The grates, draft, combustion chamber, etc., suitable for one kind of fuel may not be at all suitable for another, and the insurance of a uniform fuel supply is not within the power of the user of fuel in comparatively small quantities. It is only large plants which buy fuel at wholesale that can afford to have a guaranteed and uniform supply. The purchase of fuel under specifications is a refinement in fuel practise that has come into very considerable vogue within the past five or ten years. It is only such plants as use fuel in large quantities that can avail themselves of the uniformity of fuel supply which the purchase of fuel under such specifications will insure.

Some of our larger central stations have found that uniformity in the size of the particles of fuel has an important bearing on

the economy with which it can be burned under boilers. In some plants it has been demonstrated that it is economy to screen the fuel so that dust and small particles may be separated from the larger and burned in a separate furnace particularly designed with that end in view. It is evident that only a plant having a comparatively large fuel consumption can afford to enter into such a refinement in the use of its fuel. Here is another economy that is available only in a larger plant.

After fuel, labor is the next largest of the items that go to make up operating cost. In the large plants it is possible to introduce labor saving devices, that would be out of the question in the small plant. Probably one of the greatest labor saving devices in the modern power plant is the mechanical stoker. Not only does the mechanical stoker save labor but it also gives an ability to force boilers to a point not possible with hand firing. Thus an indirect saving comes from the use of mechanical stokers (in reducing boiler equipment necessary during peaks) that is as great, if not greater, than their effect in the direct saving of labor. In the small plants the installation of mechanical stokers is not justified, because, even with hand firing the boiler room force is so small that it could not be further reduced by introducing stokers.

Again, when we come to analyze engine room labor, it is evident that a 10,000-kw. turbo-generator does not require much more attention than a 100-kw. unit. Each unit has about the same number of bearings and there is little inherent reason for the large unit requiring much more attention than the small one. When we compare them on a per kilowatt basis, the large unit, of course, has a tremendous advantage in labor cost.

In a small plant we will find that the coal supply is brought in from the coal pile in a wheel-barrow and shovelled into the furnace by hand. In the large plant the incoming coal is dumped by gravity from a hopper car and carried almost automatically by machinery into bins above the furnaces where it is fed by gravity to the grates. The difference in labor is, of course, very marked, but it would be ridiculous for the small plant to attempt to use such coal-handling machinery, because the amount of labor which it could save would not begin to pay for the fixed charges on the machinery.

The removal of ashes is another point wherein the large plant has an advantage on account of its size. The small plant must have them raked out by hand, loaded into a wheel-barrow and

hauled away to a pile that is again moved by hand when a sufficient amount has accumulated. The large plant dumps them into a tram-car that takes them directly to a hopper car for disposal at once.

Another item of economy which can be exercised by the large plant, but is prohibited to the small one, is that of adjusting the apparatus to the load to be carried. A large plant usually is equipped with a comparatively large number of units and can operate them so that the units are run near their maximum economy point. On the other hand, a small plant is usually equipped with a relatively small number of units and must often run a unit considerably larger than necessary to take care of the load and consequently operate it at a relatively low point on its economy curve.

And so one may go on indefinitely and enumerate the advantages and economies of the large central station. If the boiler feed water is bad, the large plant can afford to install a water softening plant; the small plant cannot think of such a refinement. The large station can afford to insure itself against a coal miners' strike by installing a coal storage yard, and to insure itself against electrical breakdowns by spare units, spare cables and a double set of buses—refinements that would be entirely out of reach of the individual small plant.

It is evident, therefore, from the foregoing analysis, that not only does the central station have an advantage in first cost but that it has a much greater advantage both in operating cost and in the ability to insure continuity of service.

3. Diversity Factor

Now we come to the third advantage of the large central station serving a diversified load. As the name indicates, diversity factor might be defined as the advantage in capacity which is secured by the large plant serving many different kinds of loads over the aggregate capacity of the many plants that would be required to serve each individual part of this load separately. Not only is the large station cheaper per kilowatt than the small one, but also the large plant does not have to have as many kilowatts of capacity installed to take care of a given aggregate load as would individual plants for taking care of the same service.

The diversity of two or more loads may be complete or only partial. Diversity may also occur on account of either yearly

or daily fluctuations in the time that the maximum of a given load occurs. As an example of yearly fluctuations we might cite, as summer loads, ventilating fans, irrigation, pleasure parks and ice making; as winter loads, electric heating (as for street cars and houses) and electric lighting during the early hours of the daily lighting period. As examples of diversity factor due to daily variations we might cite power for the operation of factories during the day and the power required for illuminating the streets at night. These are examples where the diversity is nearly, if not quite, complete, as there is no coincidence whatever of the times at which such loads must be carried.

Partial diversity is always secured between two loads unless the loads vary in exactly the same proportion at exactly the same time. Such a coincidence is impossible, and as a consequence any loads will have some diversity in the times at which their maxima will be taken.

One of the best examples of diversity that the writer knows of is the use of one of the United States Government irrigation plants in the west for house heating during the winter months—a use which was called to my attention by Mr. O. H. Ensign, Chief Engineer of the United States Reclamation service. The power plant in this case was installed primarily for the purpose of pumping water for the irrigation of some of the arid lands of Idaho. The irrigation season in Idaho opens in April and closes usually in September, operating for this purpose only during the summer months. During the winter months there is ample water to run the plant and practically the only expense of its operation during the winter is the labor necessary for attendance. It is evident that the machinery will have less depreciation if operated during the winter months than if simply shut down and left uncared for. There is not the same chance for the apparatus to absorb moisture and it will unquestionably be in a better shape for this operation than if not operated during the winter.

In this Idaho irrigation district, advantage is taken of this condition by supplying electric heat to the farmers during the winter months at a price that will simply pay the cost of operation. This policy results in a price of the order of one-tenth cent per kw-hr. With such a price, one dollar will buy 3,420,000 B.t.u. With coal running 10,000 B.t.u. per lb. and selling at $4.00 per ton (which is certainly a favorable statement of the fuel conditions in this district) one dollar will buy 5,000,000 B.t.u. An

efficiency of 50 per cent is certainly all that can be expected in burning fuel for house heating purposes, while with electric heat one cannot avoid an efficiency of 100 per cent. As a consequence, we have the condition where the farmers of Idaho are able to heat their houses by electricity actually cheaper than by coal, to say nothing of the greater convenience and cleanliness of the electric method of heating—and this all comes on account of the existence of diversity factor.

Complete diversity occurs only with certain limited kinds of service; partial diversity occurs on every kind of service. The amount of partial diversity which occurs depends entirely upon the nature of that service. Mr. H. B. Gear, in an interesting paper read before the Chicago Section of this Institute in 1910, gives some valuable data on the question of diversity factor. He found, for instance, that in residence lighting the diversity factor amounted to over six, that is, the sum of the maxima of a considerable number of residences was over six times as great as the maximum required from the generating station to serve all of these residences. For commercial lighting, that is, the lighting of retail stores, etc., he found a diversity of nearly 2½; for small scattered service he found a diversity of practically the same figure and for large users the diversity was still 1.4. Possibly this last figure is the most significant of all. It is the large user who would be tempted to install a plant for his own operation. Residence lighting and small scattered power, etc., use such a small quantity of energy that there is practically no incentive for such users to provide their own power. However, the fact that the large user still has a diversity as high as 1.4 is, of itself, sufficient to enable a large central station to supply power to such users cheaper than they can make it themselves. This one consideration, independent of the others that are discussed in this paper, is sufficient to justify the central power station, because it means the installation of less than three-fourths the amount of apparatus in a central station than it would require in separate individual plants for giving the same service.

Even where various services are of the same kind there is a considerable amount of diversity. Mr. Samuel Insull, in an interesting and instructive paper read before this Institute in April, 1912, has shown this to be true. He finds, for instance, that the diversity for the operation of the various steam railroads centering in New York is of the order of some six or eight per cent. When it is borne in mind that this is the diversity for the same

kinds of service, it is evident that the diversity between different kinds of service will be very much greater. It is important, therefore, that a central station diversify its service just as far as possible. For instance, a plant whose main business is to supply lighting and general power can take on a railway load more economically than can a plant whose output is already being taken by railroads. On account of the diversity between these different types of load, the addition of a railway load may be assured by a plant already carrying a general power and lighting load with the addition of less apparatus than required by a separate plant to serve the same load. Concentration of power supply makes for economy in every aspect.

There are two arguments that may, with reason, be urged against the central station method of supply. The first is that the central station requires the addition of a transmitting and distributing system before its customers can be supplied, and the cost, upkeep and losses in this transmitting and distributing system must be added to the central station to make it comparable with individual customers' plants. This argument is entirely legitimate, as far as it goes, but it does not go far enough. The cost and losses of the transmitting and distributing system do not amount to enough to begin to offset the advantages on the part of the central station that have been detailed in the preceding pages. It is, of course, possible to imagine a condition where the cost and losses of transmission and distribution make the central station supply more expensive than an isolated plant, but this means that we have gone beyond the proper radius of that station. The advantages (in the matter of cost) of the central station are so great that the utmost addition, on account of transmission and distribution, and still maintain good regulation, is not sufficient to permit isolated plants to compete.

The second argument in favor of the isolated plant is that during the season that heating is required the steam may be used twice, once for power and the exhaust for heating. This is also a legitimate argument so far as it goes and its complete discussion requires much more space than I have at my disposal here. In general, however, it can be shown that the advantages which accrue to the centralization of a large amount of power at one point will far outweigh the advantage of the isolated plant even when it is coupled with the heating proposition, as it so often is.

When the isolated plant is used for heating, we must bear in

mind that there is a large part of the year, certainly more than one-half of it, when no heating whatever is required and during this period the plant must accept the losses which are inherent with the combination of power generating and steam heating plant using the same steam. Another thing which must not be forgotten is the daily diversity between the heat and power loads in the isolated plant. Take for example, the case of an office building. The building will, of course, cool off to a certain extent during the night and it is required that it be brought to a certain acceptable temperature by the time the office force arrives in the morning. This will require a considerable amount of steam during the early morning hours, at which period there is absolutely no use for light in the building and practically none for power. The heavy demand for light and power in this same office building will occur just before the force is getting ready to leave for the night and at this particular period of the day the requirements for heat are at a minimum because the heat inertia of the building is sufficient to keep up the temperature at this time, and it is useless to put in more heat at the time when the force is getting ready to leave. Therefore, while it is perfectly true that the same steam can be used economically for lighting and heating, it is impossible to so arrange a combination plant of this kind that the diversity in time requirements for the different kinds of service make it possible to make complete use of this advantage. This is a case where diversity works against and not for economy.

As a result of the foregoing analysis, the writer is of the opinion that there are only two reasons why central stations should not supply all of the electrical service within legitimate reach of their distributing systems. These are, first because the rate offered by the central station does not bear a suitable relation to the cost of the service to be supplied, and

Second, because the prospective customer has some motive other than the cost of the supply for not taking his service from the central station.

DISCUSSION ON "RELATION OF PLANT SIZE TO POWER COST" (LINCOLN), PHILADELPHIA, PA., OCTOBER 13, 1913.

Harry Archer Hornor: Mr. Lincoln has properly stated in the introduction of his paper "that most engineers are ready to admit without argument that a large power plant can supply a given power service as a part of a general power supply business more economically than a plant merely equipped for special manufacturing business." Therefore it is obvious that we should look to other than engineering considerations to find the motives which prevent the prospective customer from purchasing his power from a central station.

The author of this paper presents two arguments that may be urged against the central station method of supply. The first of these arguments, namely the question of the transmission and distribution of power, may easily be dispensed with because of the increasing number of central stations in congested communities, as well as the development in the art of very high potential distribution over long distances. Factories today are rarely placed without the zone of a central station. The promoters of an industrial venture would take into consideration the question of the advantages of such power supply in selecting a site for their plant. I doubt very much whether the central station would have been given as much consideration say ten or fifteen years ago.

The author's second argument in favor of the isolated plant, namely, the use in most industrial companies of steam, must indeed have careful consideration. This argument seems to be the last one which is of direct importance to the engineer. Many industrial plants not only require steam for heating purposes throughout their plant and offices but also employ it in various parts of their manufacture. No doubt the use of steam in this way is extremely uneconomical, and no doubt other forms of energy could be just as well applied. Furthermore, it may be purely because the steam plant is there that steam is so used. Nevertheless the fact that a conversion to some other form of energy must now be made, causes the owner to consider very carefully the cost of this substitution. We see how quickly the problem changes from that of engineering into commercial economics.

Mr. R. S. Hale, in a paper read before a joint meeting of the American Institute of Electrical Engineers and the American Society of Mechanical Engineers held in Boston, February 16, 1910, points out a condition which I dare say would be found in a majority of isolated plants, namely: whereas the central station would figure its cost of power too high the isolated plant would be apt to figure its cost of power too low. This problem would be an extremely easy one and very definite of solution if the isolated plant only manufactured one kind of

power. As a matter of fact the large manufacturing concern, especially one doing a varied business, must equip the plant with many different forms of power. Mr. Lincoln has pointed out that this is exactly the place where the central station can aid because the diversity factor is large and the generating units would naturally be in proportion, making their first cost relatively high. On the other hand the isolated power plant would be under one operating force and under the same accounting system, which would make it difficult in most cases to determine the individual costs of power without a very elaborate system of bookkeeping.

The manufacturing company with which I am connected uses four different kinds of power for its construction purposes, namely, electric, pneumatic, hydraulic and steam. All these forms of power are generated in the same power-house and with the same operating force. It would not be possible to determine definitely the unit cost of any one of these without an elaborate installation of instruments, a special piping system and a particular system of bookkeeping. Let us take the electric power alone: Two double-current generators are daily providing the electric power. These units are rated at 500 kw. and carry a regular load throughout the day of about 600 kw. or 20 per cent overload. They are therefore operated normally at good efficiency as far as the generator is concerned. There is also installed one 500-kw. direct-current generator. This generator is also used for what might be called peak lighting load. The switchboard operator throws the two double-current generators into the distributing system in the morning, shuts them down at noon, places them in service after the noon hour, and shuts them down at quitting time, except in the event of the plant working overtime. This switchboard operator is as a matter of fact an oiler. Since there has been installed a voltage regulator he has no more duties as regards the running of the electric plant than those above outlined. If central station energy was substituted for the electric plant, there would be no reduction in operating force.

Let us consider the problem in another way: The electric power consumed seems to bear a relation, something like 20 per cent, of the total power with the exception of steam. As we would not reduce our operating cost, and could only look for a reduction at the coal pile, the immediate commercial question that would be asked is, would we reduce the amount of coal purchased per year by twenty per cent, and how much money would this represent when we include the amount paid by the year to the central station? For the plant in question, and with the data that is available I am of the belief that there could be no commercial consideration given to this proposal unless the central station could supply electric energy so that no more operating expense to the customer would ensue, and that the cost per kilowatt-hour would be less than one cent. If the plant used

alternating current it would only be necessary to install an industrial substation equipped with static transformers. This would answer the first part of the question. As it happens, approximately one-half the load is direct current, generated at 230 volts, and the other half is two-phase 25-cycle, 200-volt, alternating current. This would necessitate either the conversion of the present plant or the installation of synchronous converters. The power house as now designed would not permit the installation of any additional apparatus, so that parallel operation with the present machinery would only be possible by the erection of a separate building involving a separate operating force.

The next consideration is then, the substitution of electricity for producing all the power, so that the present power house could be completely dispensed with and an electrical substation substituted. This involves a number of interesting considerations into the detail of which it is not possible to fully enter. Briefly, this comprises the question of rotary hydraulic pumps; rotary air-compressors and the question of heating. This latter, though possible of accomplishment by means of electricity, will, I think, be generally admitted to be an expensive substitution, although as Mr. Lincoln has stated the small plant does not reach a point where it pays to install certain economical devices for the production of steam, yet on the other hand there are certain practical economies which can be introduced by which wastes of various kinds, though not entirely eliminated are very much reduced. This makes it problematical in the minds of the owners of such plants, to maintain their plants up to a point where either developments compel a change, or depreciation is so great that the apparatus can no longer sustain the demands put upon it.

It may appear from the foregoing that this is an argument for the isolated plant and against the central station. Such is in no sense the intention. It is rather an endeavor to find the reason which prompts men who own isolated plants to retain them in preference to the purchase of power. The central station may be a little to blame in not making special efforts in this direction.

Granted that they have at the present time accomplished much, I cannot see but what it depends greatly upon whether they wish to accomplish more. If the central station, as Dr. Steinmetz recently stated in an address before the Franklin Institute this month, can find an off-peak power load that does not cost them the installation of more apparatus and additional operating expenses, it is safe to say that the central station could sell its power at even as low a rate as mentioned by Mr. Lincoln in his illustration of diversity factor as shown by the United States Reclamation Service in the Idaho Irrigation System. But if, as we have recently heard it proposed, the central stations take over the power supply to railroads for the electrification

of surburban lines, I do not see but what the central station will be required to install and operate more apparatus, because this load will undoubtedly strike the peak, as the busy people will be going to and from their work at the same time that the station will need to supply its peak load.

This is an interesting subject because it is such a large one and so many different factors enter into every side from which you view it. Although steam central plants have shown a wonderful reliability as well as flexibility, it has not been very long ago that a friend of mine in the northeastern part of this country very seriously considered annulling his contract with a water-power central station, and installing a plant of his own. I believe, however, that it is generally recognized to-day that such central stations, subject by the elements to an interruption of service, must parallel their water turbines with a steam plant, because of this uncontrollable consequence.

I notice that Mr. Lincoln in his paper did not touch particularly upon this point, and I suppose he did not because such eventualities are not so frequent. It is nevertheless a very important motive in any manufacturing concern whose product depends entirely upon the supply of electric current.

As a summary I should deduce the following:

First, the promoters of any new manufacturing venture would today consider the location, and operation of their industrial plant so that central station power could be used. This would be considered in their estimate of first cost, expense of operation, and in their original design.

Second, for those owners who are now operating isolated plants supplying various powers including steam, convincing reasons must be presented whereby they may abandon their present plant entirely and economically purchase their power.

Third, I believe the principal motive underlying the retention of the isolated plant is due to commercial economy rather than to engineering principles.

Fourth, I believe that the central station in its development will overcome all obstacles and reduce the number of isolated plants.

Fifth, I also believe that in the case of very large vessels that a central station adapted for this special service will be installed, and that requisite power will be delivered both for the driving of the vessel and for the operation of her auxiliary machinery.

W. C. L. Eglin: Mr. Hornor seems to take up one or two questions on the other side. There is a fourth point that occurred to me while Mr. Lincoln was reading his paper, and that is, the depreciation of any apparatus. The consumer invariably has his mind fixed on the efficiency shown by his apparatus when first installed and tested; and he still believes it is operating at the same point of efficiency after several years of use. The central station company generally finds that it pays to discard such apparatus and install more efficient apparatus. That is

very clearly shown in all the larger stations; whereas with the individual owner of a small plant, some particular change in his business or the extension of the business to the point where the plant becomes too small for his needs, would be required before he would think of abandoning it.

The next thing is the inertia to be overcome. Take the case of the tungsten lamp: It is three times as efficient as the carbon lamp, yet there are three times as many carbon lamps sold today as there are tungsten lamps. The people are not installing as many tungsten lamps as they should, and it will take from three to five years to educate them to do so. In Europe you will have a task trying to find a carbon lamp. You see them, it is true, but you see many more tungsten lamps than carbon, while in this country you will see more carbon lamps than tungsten.

It is only a matter of time before the central station must be extended to the point where its service will become practically universal.

That is the real objection to the substitution of electrical service from the central station—you must have a property large enough to be able to afford to "scrap" apparatus, even to the extent, sometimes, of removing the entire plant investment from your books. It is hard to get the ordinary manufacturer to throw out his plant and "forget about it."

P. V. Stevens: I ask Mr. Lincoln for my own information, and possibly for the sake of others, this question: The discussion or treatment in this paper has been apparently referring to steam plants, and the majority are familar with the conditions met in such plants, but assuming the advantage of the large central station over a small station is 10 per cent, I would like to know what percentage would represent the advantage in the operation of oil and gas plants where the fuel is relatively cheap.

C. O. Mailloux: This paper discusses the general case very comprehensively and intelligently. When we come to special cases, certain modifications may be necessary in the reasoning and in the conclusions, as the author has himself pointed out. We all agree, for example, in regard to the general statement that the economy of a plant will be a direct function of its size. There are, however, considerations which often argue in favor, and demonstrate the superiority, from a financial standpoint, of a small individual plant—the so-called "isolated plant."

My experience with isolated plants covers a period of over twenty-five years, and it is so diversified that I cannot now give more than a general summary of it. As consulting engineer, I have had, during that period, to deal, in some technical capacity or other, with perhaps a thousand isolated plants, large and small. In more than half of these cases, I have had charge of the design and installation of the plant, and in a number of cases I have also had charge, for a time at least, of its operation.

I have also had occasion to make reports in regard to the feasibility and economy of isolated plants in hundreds of cases. In the latter cases, the question was gone into most thoroughly; a very careful, honest attempt was made to get at all the facts and figures bearing on the case, in order to reach the true and correct answer as to whether the plant would pay or not. In many cases, the answer indicated that the plant would not pay; but in many others it showed definitely that the isolated plant was warranted. I will only refer now to those instances where there was absolutely no chance for the central station to replace the isolated plant.

A very interesting case was that of a large sugar refining establishment in Brooklyn, in which a boiler plant of about 10,000 h.p. was rendered necessary because of the immense amount of evaporating to be done incidental to the sugar refining operations. This large boiler plant would have to be there anyhow. The same boiler room force and the same facilities would be necessary whether the electric current supply required for lighting and power came from an isolated plant or from a central station.

At the time this plant was designed, the question of electric current supply received careful consideration, and it was soon made obvious that the cheapest and most practical way would be for the establishment to produce its own power, by generating steam at high pressure, say 150 lb., and reducing this pressure to that which is required for evaporating, namely, from 7 to 12 lb., by passing the steam through a simple engine designed to operate under a back pressure of 7 to 12 lb. Now under those conditions, a simple engine would not be particularly economical, as we know, but looking at the matter from the standpoint of thermodynamics, and considering the amount of energy abstracted from that steam in being thus "throttled" from 150 lb. pressure down to about 10 lb. pressure, while passing through the engine cylinder, one finds that the steam loses only a very small percentage of its total energy, (the actual theoretical loss is only about 3 per cent for the above conditions); and yet in falling by expansion from 150 lb. to 10 lb., it is capable of generating a great amount of power. The plant was installed and was a great success. It has been running more than 15 years, developing somewhere between 1500 and 2000 h.p., through engines operating direct-connected dynamos which supply electrical energy sufficient to operate the lighting system and for all the electric motors of various sizes required in the different buildings. In a case like this the cost of fuel and boiler room attendance are reduced to an insignificant amount. The only items that enter materially into the cost of the electric power are the cost of engine and dynamo attendance, and the fixed charges on the cost and also the maintenance of the engines, generators, dynamo leads and switchboard; and considering the large output obtainable from the plant, it is apparent that the cost of electrical energy per kilowatt-hour must be very

small. That concern is one of the few in New York City that can afford to use electricity for cooking. It literally has electricity to burn. An electrical cooking installation was put in which has been in operation since the plant was started, and which serves daily for cooking the lunch for a large force of men, composed of the heads of various departments. My recollection is that the cost of electric current was somewhere around 2 or 3 mills per kw-hr. It would, of course, have been impossible for any central station plant to compete with such an isolated plant.

There are many other cases where the isolated plant proves to be cheaper for the consumer than the central station current supply. I have found this to be true in scores of cases, as in large office buildings, where steam heating is required during many months. Mr. Lincoln says that no heating is required for more than half the year. My own experience leads me to a different conclusion. In these latitudes, one must figure on heat being required in a building for at least seven months. Most of the time during that period, the fuel consumption which is properly chargeable to the electrical service when high pressure steam is used, and the cylinder of an engine is employed as a throttling valve to bring the steam pressure down to three or five pounds, is small because, as already seen, the energy abstracted from the steam by that throttling process is very small. Even assuming that there may be a certain time during the 24 hours of the day when one must use steam that is not chargeable to the heating system, yet the total cost of the coal and of the boiler room attendance chargeable to the electric service in the winter months is very small. This matter has been investigated by me, or under my direction, in many scores of cases. In some instances we have been able to corroborate the conclusions of our investigations. There were cases where the current had been supplied from a central station and return was made to the isolated plant. In other words, we have had cases where the same building has been operated under the same conditions, both by current from a central station and by current from its own isolated plant. We have also had cases where the steam for heating as well as for power was taken from the central station in New York which furnishes steam to consumers through underground mains. We have been able to make comparisons of cost in instances where an abundance of good and reliable data was available to enable us to check up the results and conclusions very carefully. One interesting instance was the building in which my office was located for a number of years. In this case the isolated plant, after being operated for a certain period of years, was stopped. Electric current was taken from a central station and steam for heating was taken from the underground steam mains. The total cost of the service proved to be considerably higher than expected, and eventually a return was made to the isolated plant, which has since then remained in operation.

A careful study of the facts and figures, taking into consideration every factor bearing on the case, including depreciation, obsolescence, rental value of space, and all like conditions, showed that it cost the building less to produce its own supply of electricity and steam than to take it from the street mains.

I think that Mr. Eglin's remarks in regard to lamp economy have an important bearing upon this situation. It now seems possible that we shall be able to reduce the lighting load of a plant to a great extent with lamps giving a candle power with ½ watt. Under those circumstances, the electric load, especially in buildings where electric current is used almost entirely for lighting, will be greatly reduced. While this does not make much difference in the winter months, yet it will make considerable difference in the summer months, because the expenses which are fixed, such as the cost of labor, interest on plant, etc., then become relatively large and increase the cost per kw-hr. materially. Under those circumstances, the isolated plant, while still effecting a saving during the winter months, might represent a loss during the summer months. I therefore expect that the improvement in efficiency of incandescent lamps will help to bring about the gradual elimination of isolated plants.

I am in accord with the feeling that the number of isolated plants will go on diminishing. It seems to be in harmony with the nature of things, and with the principles which Mr. Lincoln has so clearly set forth in the first part of his paper. I cannot quite assent to the proposition that they can be all eliminated at the present time. It is my belief that there are many, indeed thousands of cases, where the isolated plant is still cheaper than the central station. I would not say, however, that the time will not come when we may speak of an isolated plant as having been relegated to the museum of ancient things.

M. G. Lloyd: As one engaged in a weekly endeavor to demonstrate the desirability and feasibility of central-station service I have been much interested in Mr. Lincoln's paper. He has demonstrated his main thesis, viz., that power can be generated at less cost in a large plant than it can in a small plant, but as he grants in the last two pages of his paper, that is not all there is to the question of installing central-station service.

I am sorry we have not more figures on the question of what the cost of distribution is, as I believe it to be a much more important item than the author has indicated. I think I remember that a representative of the Baltimore central station at one of our former meetings made the statement that the investment in the distribution plant in that city was greater than in the generating plant. In Chicago this is undoubtedly true and the distribution system there has probably cost 30 or 40 per cent more than the generating plant. Consequently the fixed charges on this portion of the investment are greater than the fixed charges upon the investment for power house and there will also be an operating expense for distribution which will

cover the power loss in cables and maintenance cost for this portion of the system. This results in an important item of the total cost which the isolated plant does not have to include in its computation.

One of the standard arguments for the isolated plant is the economy of combining the use of steam for heating and for power generation. Mr. Mailloux has already shown that there are cases where that is sufficiently advantageous to over-balance any advantage the central station may have in other respects. Mr. Lincoln has rather weakened his argument on this point by limiting the period during which buildings require heating to six months; in my territory (Chicago) heating is required for fully eight months. While heating is not actually required every day during this period it is necessary to have steam up and ready to turn on in case of a sudden turn to cold weather. It is true that the load curve for heating is, however, not coincident with the load curve for power, but that does not affect the question of cost so much as the point of whether the peak loads coincide. Mr. Lincoln claims that the heating load in many instances falls off entirely before the power peak comes on between 5 and 6 p. m. This is not true of office buildings, which must be heated well into the evening.

I should like to take exception to one minor point in the paper where diversity factor is referred to. In order to have a diversity factor of unity the author claims that the loads must be proportional at all times. I do not think that statement can be upheld, because even though the load curves may be entirely different in two plants having the maximum in each case at the same time there is no diversity since the generating equipment must be sufficient to supply that maximum and the diversity factor will be unity, although the load factors of the two plants are entirely different.

Central-station solicitors realize that if their business depended only on the three main propositions brought out in Mr. Lincoln's paper they would have no difficulty in getting all the customers that were solicited. Other points have to be met, however, and while it may not have been within the province of Mr. Lincoln's paper to discuss these, still they must be considered with respect to central-station service. His arguments are getting stronger every day, owing to the ever-increasing size of the central station, and its units, which are now up to the point of 20,000 to 35,000 kilowatts. The central-station man can make his case stronger in every instance where he has the best of the argument if he realizes fully the arguments upon the other side and is free to admit that there are cases where the central station cannot compete with the isolated plant.

C. O. Mailloux: I think that the previous speaker overestimates the importance of the increasing size of the central station units. The total cost of delivering the service from the central station is not made up of the central station cost plus fixed

charges, but is made up of the total central station cost plus the cost of delivery. Now the cost of delivery, it happens, is very much greater than the cost of producing the energy. The most that can be expected as the result of increase in size of the units is an economy of a few mills per kilowatt-hour. If the cost of electrical energy at the busbars in the central station is, let us say, 55 mills per kw-hr. we may be able to get it down to 45 mills or even to 35 mills. There is an "asymptotic" value somewhere, which is probably between three-tenths and four-tenths of a cent. To this must be added the cost of transmission and distribution. The further economies realizable must be effected mostly in the cost of distributing the electrical energy supplied to the consumer, which is never less than 0.5 cent to points nearby, and it may be two, three or four cents to remote points.

It seems to me that we cannot hope for much from the increased economies resulting from the increased efficiencies in the central station. In a case where the bulk of the cost is for electric power (for electric elevators, ventilation, etc.), the conditions will not be more favorable to the central station, but more likely will be less so. The conditions which may make a great decrease in the load of the isolated plant will arise especially in cases where the bulk of the service is for lighting.

J. P. Jackson: Many plants that you would consider competitive in any way, may be so small that it would not pay to put in feed-water heaters, etc. But I judge that with any plant so small that it would not need such auxiliaries, there is no question but that it would be more economical to go to the central station for power. Certainly very small primary power generation units are as a rule very undesirable, when central station power can be obtained at suitable rates.

I would like to emphasize Mr. Eglin's statement about the depreciation in figuring out the cost to an isolated plant. The specialist emphasizes the necessity of improving everything. I imagine the man who puts up the money in the plant sees very dimly that the actual plant is decreasing or depreciating due to the improvement of the art. His plant is running all right, and he does not like to be told that it is depreciating on account of advance in the art.

There is another thing I believe it is worth while to mention specifically and that is the lucid, clear statement of these subjects which our friend Mr. Lincoln uses. He has an extraordinary way of putting things, so that a layman, like some of us, can understand what he is saying. I believe if the engineers would confine themselves to a simple, clear intelligible statement of the principles of science and engineering, that engineering would advance with greater rapidity than otherwise.

Finally, permit me to say that I am on the side of the central station. I believe the central station is bound to be the great source of power in the world; but I also believe with Mr. Mail-

loux, that each case must be studied out on its merits, and no general statement of the facts should be accepted. Mr. Mailloux is right, that buildings having lighting, heating and other loads to carry might be different in their relative conditions from others.

G. J. Blum: It seems to me that the discussion has brought out a point worth considering and that is that the central stations while trying, so to speak, to get nearer to their customer, are in reality getting further away from him. I refer to the concentration of generating equipment in a very few very large power houses which in many cases are located at an average great distance from the points of greatest load, thus entailing high fixed and high maintainance charges on distribution equipment.

A reasonable increase in the number of generating stations so located in reference to load centers as to reduce line losses and cable troubles to a minimum and to make possible an alternative selection at the substations, especially the large industrial substations referred to tonight, in case of trouble on any particular feeder, would in the speaker's opinion make much more remote the possibility of any interruption of industrial service dependent on central station supply. The matter of steam heating service from such central stations would further suggest itself as a possible source of revenue.

I think it is along these lines that thought might be directed by those men responsible for the most profitable operation of the central station.

P. M. Lincoln: The point is well made by Mr. Hornor and Mr. Eglin, that the central station not only must show economy in serving a new customer but that often in the case of an existing isolated plant, the central station must have charged against it the fixed charges on the plant that is displaced by the use of central station power. It is an endeavor to show a saving after a scrapping of the old plant which breaks the back of the central station.

The paper I have prepared necessarily deals with generalities, and contemplates the conditions necessary to compete when no isolated plant exists. When we deal with the conditions of an isolated plant already built, the margin in favor of central station power is much reduced and sometimes wiped out.

Mr. Eglin mentions the fact that carbon lamps were scarcely seen abroad while very frequently used in this country; and I looked at the lights used in this room and I find they are carbon lamps. Here is a case in point where carbon lamps are in use, and where tungsten lamps would undoubtedly save a considerable amount.

Mr. Stevens has asked a question as to the possible competition between central station plants and isolated plants that use oil or natural gas for fuel. The best answer I know of to that is to point to the scarcity of such oil and gas plants. Theoretically the Diesel engine or the gas engine can do better than the cen-

tral station steam plant in the matter of thermal efficiency. However, the handicap against them in other directions is such that they have made comparatively little headway.

Mr. Mailloux cites a case where the central station plant would have no chance at all. His sugar refinery required large quantities of steam for the vacuum pans for evaporating, and there was consequently a large boiler plant, and the small percentage of steam that was taken in generating the power made the power cost comparatively slight. It takes very little more heat to turn out steam at 150 lb. pressure than it does at 15 lb. and the power that can be obtained in throttling down from 150 lb. to 15 lb. is a by-product which costs practically nothing. In that case I do not think central-station power would stand a ghost of a show.

I note my estimate of the time during which heat for buildings is required is questioned. My estimate was based on conditions as they exist in my own house. I start my furnace about October 15th and stop about April 15th. If I should count from the time it is first started to the time when it is last used, it might be somewhat more than six months; but there are warm fall days and warm spring days when the furnace is not required. Now the requirement for heating in the usual building in the main covers about the same period of time. There is a further fact which I did not emphasize in my paper, that the maximum heat requirements for zero weather are tremendously greater than the average. This fact entails a very decided additional difficulty in using the same steam for both heat and power.

In answer to the comments of Mr. Mailloux and other gentlemen, let me point out the first of the requirements I set forth in the last page of my paper; I there call attention to two reasons why central-station power might not be used to supply all of the electrical service within legitimate reach of their distributing systems. The first of those reasons is, that the rate offered by the central station does not bear a suitable relation to the cost of the service to be supplied. I believe that the increased use of central station power that will surely come as time goes on will reduce its cost very considerably from what it has been in the past.

Mr. Lloyd mentions the fact that the cost of distributing central station power is very considerable, which is true. In one case I figured the distributing cost ran from 60 to 70 per cent as much as the cost of the power itself. But that cost enters into fixed charges only. The distributing system "eats no coal" except what may be due to the losses therein, which are comparatively small. The additional cost of central station power on account of distribution is not sufficient, in general, to justify the isolated plant.

Presented at the Chicago Section Meeting of the American Institute of Electrical Engineers, Chicago, Ill., October 29, 1913.

Copyright 1913. By A.I.E.E.

INSTABILITY OF ELECTRIC CIRCUITS

BY CHARLES P. STEINMETZ

During the earlier days of electrical engineering practically all theoretical investigations were limited to circuits in stable or stationary condition, and where phenomena of instability occurred, and made themselves felt as disturbances or troubles in electric circuits, they either remained not understood, or the theoretical study was limited to the specific phenomenon, as in the cases of lightning, dropping out of step of induction motors, hunting of synchronous machines, etc., or, as in the design of arc lamps and arc lighting machinery, the opinion prevailed that theoretical calculations were impossible and that design by trial only, based on practical experience, was feasible.

The first class of unstable phenomena which was systematically investigated, was the transients, and even today it is questionable whether a systematic theoretical classification and investigation of the conditions of instability in electric circuits is yet feasible. Only a preliminary classification and discussion of such phenomena will be attempted in the following.

Three main types of instability in electric systems may be distinguished:

1. The transients of readjustment to changed circuit conditions.

2. Unstable electrical equilibrium; that is, the condition in which the effect of a cause increases the cause.

3. Permanent instability resulting from a combination of circuit constants which cannot co-exist.

(1) Transients

Transients are the phenomena which occur at the change of circuit conditions, when current, voltage, etc., readjust them-

selves from the values corresponding to the previous condition to the values corresponding to the new condition of the circuit. For instance, if a switch is closed, and thereby a load put on the circuit, the current cannot instantly increase to the value corresponding to the increased load, but some time elapses, during which the increase of the stored magnetic energy, corresponding to the increased current, is brought about. Or, if a motor switch is closed, a period of acceleration intervenes before the flow of current becomes stationary, etc.

The characteristic of transients therefore is, as implied in the term, that they are of limited, and usually of very short duration, intervening between two periods of stable conditions.

Considerable theoretical work has been done, more or less systematically, on transients, and a great mass of information is thus available in the literature. However, to some extent, the transients of our theoretical literature are still those of the "phantom circuit"; that is, a circuit in which the constants r, L, C, g, are assumed as constant. The effect of the variation of constants, as found more or less in actual circuits, viz., the change of L with the current in circuits containing iron; the change of C and g with the voltage (corona, etc.); the change of r and g with the frequency, etc., has been studied to a limited extent only, and in specific cases.

In the application of the theory of transients to actual electric circuits, considerable judgment is thus often necessary to allow and correct for these "secondary" phenomena which are not included in the theoretical equations.

Especially deficient is our knowledge of the conditions under which the attenuation constant of a transient becomes zero or negative, and the transient thereby becomes permanent, or becomes a cumulative surge, and the phenomenon thereby is taken out of group one and falls under group three or group two of unstable systems.

(2) Unstable Electrical Equilibrium

If the effect brought about by a cause is such as to oppose or reduce the cause, the effect must limit itself and stability be finally reached. If, however, the effect brought about by a cause increases the cause, the effect continues with increasing intensity, that is, instability results.

This applies not to electrical phenomena alone, but equally to all other phenomena.

For instance, if in a motor, by increase of load, the torque becomes less than the load, the motor slows down. If now the decrease of speed of the motor increases the motor torque—as in a series motor—the decrease of speed stops at the speed at which the motor torque has become equal to the load. Thus, the decrease of speed limits itself, and a stable condition is restored at a lower speed. If, however, the decrease of speed of the motor decreases the motor torque—as in an induction motor below the maximum torque point—the decrease of the motor speed causes a still greater reduction of the motor torque below the load, and, therefore, a still greater slowing down of the motor, and thus with increasing rapidity the motor speed decreases until the motor stops; a condition of unstable equilibrium.

Such instability is usually the result of the system; that is, the combination of elements, but is not inherent in any of the elements. For example, in the above instance of the induction motor, while the part of the induction motor speed-torque curve below the maximum torque is often called the "unstable branch", this is true only relatively. If, with the decrease of the speed of the motor due to an increased load, the load would also decrease, and if the load should decrease with the speed at a faster rate than the motor torque decreases, (fans, ship propellers), the decrease of speed would limit itself; that is, the condition would be stable.

To illustrate more fully, in Fig. 1 are shown the speed-torque curves of an induction motor for various values of constant impressed voltage, $e_1, e_2, e_3 \ldots\ldots e_8$.

With a load requiring the same constant torque at all speeds, A, in Fig. 1, the motor could not run at all at voltages e_1 and e_2. At voltages e_7 and e_8 the motor would start and run up to a speed near synchronism, where it is stable. At voltages e_3 to e_6 the motor torque equals the load at two speeds, a_1 and a_2, on the curve e_4. The higher one of these is stable, the lower unstable. From any speed above a_2 the motor speeds up to a_1. From any speed below a_2, it slows down to a standstill. All the speeds below that corresponding to the maximum torque point c_6 are unstable with this character of load and cannot persist, but the motor either accelerates and runs up to above s_6 or slows down to standstill.

With a load requiring a torque proportionate to the speed, B, in Fig. 1 (electric generator with constant field excitation

and constant resistance of load), the motor always starts, but for voltages e_1 to e_3 never can run above a low speed (where the current is high and the efficiency and power factor low). For voltages of e_4 and above, the motor starts and runs up to a speed near synchronism. For voltage e_4 three points exist, b_1, b_2, b_3, where the motor torque equals the load; b_1 and b_3 are stable, b_2 unstable. From below b_2 the motor slows down to b_3. From above b_2 it speeds up to b_1. The motor curve now has an un-

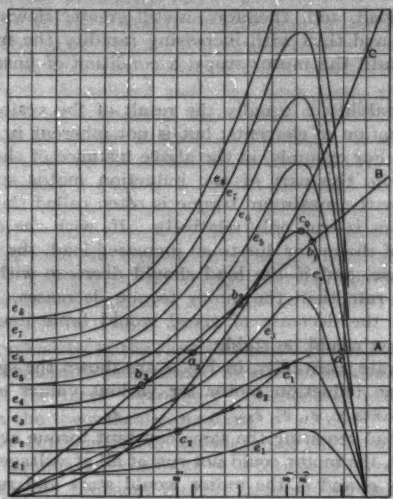


FIG. 1—SPEED-TORQUE CURVES OF INDUCTION MOTOR

stable branch between the speeds s_2 and s_1 (corresponding to the two points of contact, c_2 and c_1, of the motor torque with tangents from the origin, which for the sake of clearness have been illustrated on curve e_3), and two stable branches below s_2 and above s_1.

With a load requiring a torque proportional to the square of the speed, C, in Fig. 1 (fan, ship propeller), instability does not exist, but the conditions are always stable over the entire range

of the speed-torque curve of the motor, and the motor always starts and runs up to a definite speed, which is the only speed at which the motor can carry the particular load. With other shapes of motor torque curves—as those due to a drop of supply voltage with a decrease of speed—an unstable range may appear between two stable ranges, and in the case C also.

Probably the most important case of unstable electrical equilibrium is afforded by circuits containing an arc. It is the determining feature in the design of arc lamps, circuits and machinery, and is possibly responsible for more disturbances in electric circuits than any other phenomenon.

The voltage consumed by an arc decreases with increase of current, as shown by curve A, in Fig. 2. If then the arc is operated from a supply circuit of constant voltage, e_0, Fig. 2, and r is the resistance of this supply circuit outside of the arc, the voltage consumed by the resistance $r\,i$, is shown by B, in Fig. 2, and the total voltage of arc and resistance derived by adding A and B is given by C, in Fig. 2. As seen, two values of current exist, i_1 and i_2, at which the arc could operate in this circuit. The higher current i_1 is stable, the lower current i_2, is unstable, and the branch of the curve C below the minimum point i_0 is unstable; that above i_0 is stable.

On a constant-current circuit the arc at atmospheric pressure is stable.

Inversely, with the mercury arc in a vacuum, as the quartz lamp, instability may appear under certain conditions on a constant-current circuit, as the result of the relation of temperature and voltage. Increasing temperature increases the vapor pressure, and with it the voltage, and thus, on constant current, the power consumed by the vacuum arc. Increasing power consumption, however, increases the temperature, and thereby the voltage, and so on, and if the rate of temperature rise, due to increasing voltage, is greater than the rate of voltage rise due to increasing temperature, instability results, and the arc runs away; otherwise it is stable.

Similar phenomena, as shown by the arc, are exhibited by some solid conductors, which, in a certain temperature range, have a very high temperature coefficient; so-called "pyro-electrolytes". A typical volt-ampere curve of such a conductor is shown in Fig. 3. As seen, at voltage e_0 three values of current are possible, i_1, i_2, and i_3. Of these the low and the high ones are stable, the intermediate one i_2 unstable, and so is the entire

range between i_0 and i_0', the maximum and the minimum of the volt-ampere characteristic.

The Nernst lamp glower is such a pyro-electrolyte, and its operating current is on the unstable branch of the characteristic, therefore a steadying resistance or reactance is required, just as with an arc on constant voltage supply. Most of these conductors are chemical compounds, and at higher currents, and thus temperatures, their conduction becomes electrolytic.

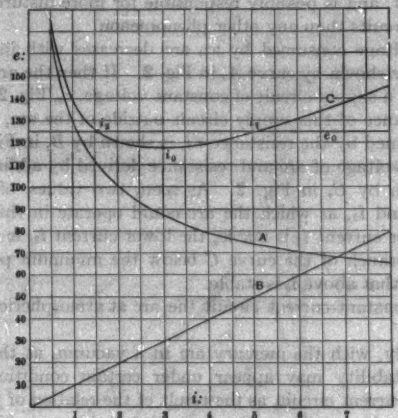


FIG. 2—VOLTAGE OF ARC

However, some elementary substances, as boron and silicon, also belong to this class of conductors.

(3) PERMANENT INSTABILITY

If the constants of an electric circuit, as resistance, inductance, capacity, disruptive strength, impressed voltage, etc., have values which cannot co-exist, the circuit is unstable, and remains so as long as these constants remain unchanged. Such instability usually leads to phenomena which are more or less periodic or intermittent.

The nature of these phenomena of permanent instability is

best shown by an example illustrated in Fig. 4. Let A and B be two conductors of an ungrounded high-potential transmission line, and $2e$ the voltage impressed between these two conductors. Let C represent the ground.

The capacity of the conductors A and B against ground may then be represented diagrammatically by two condensers $C_1 = C_2$, and the voltages from the lines to ground by e_1 and e_2. In general, the two line capacities are equal: $C_1 = C_2$, and the two voltages to ground thus equal also: $e_1 = e_2 = e$ with a single-phase, and $= \frac{2e}{\sqrt{3}}$ with a three-phase line.

Assume now that a ground P is brought near one of the lines A, but within the striking distance of the voltage e. A discharge

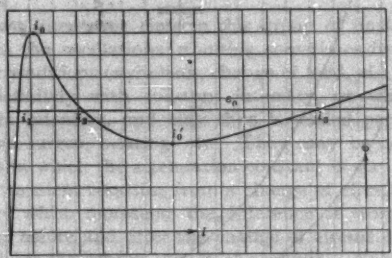


FIG. 3—VOLT-AMPERE CURVE OF "PYRO-ELECTROLYTE"

then occurs over the conductor P. Such may occur by the puncture of a line insulator, as is not infrequently the case. Let r = resistance of the discharge path P. While without this discharge path, the voltage between A and C would be $e_1 = e$ (assuming a single-phase circuit), with a grounded conductor P approaching line A within striking distance of voltage e, a discharge occurs over P, forming an arc, and the circuit of the impressed voltage $2e$ now comprises the condenser C_2 in series to the multiple circuit of condenser C_1 and arc P, and the condenser C_1 rapidly discharges, voltage e_1 decreases, and the voltage e_2 increases. With a decrease of voltage e_1, the discharge current i also decreases, and the voltage consumed by the discharge arc e' increases until the two voltages, e_1 and e', cross, as shown

in the curve diagram of Fig. 4. At this moment the current i in the arc vanishes, the arc ceases, and the shunt of the condenser C_1 formed by the discharge over P thus ceases. The voltage e_1 then rises, e_2 decreases, and the two voltages tend toward equality, $e_1 = e_2 = e$. Before this point is reached, however, the voltage e_1 has passed the disruptive strength of the discharge gap P, the discharge by the arc over P again starts, and the cycle thus repeats indefinitely.

In Fig. 4 are diagrammatically sketched voltage e_1 of condenser

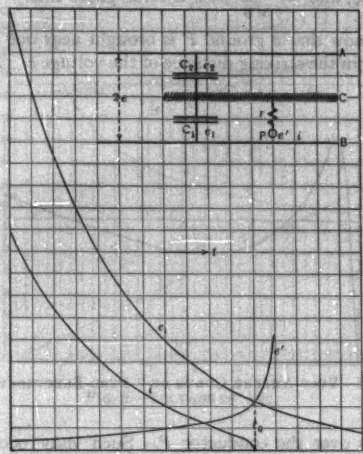


FIG. 4—ILLUSTRATING CONDITION OF PERMANENT INSTABILITY

C_1, the voltage e' consumed by the discharge arc over P, and the current i of this arc, under the assumption that r is sufficiently high to make the discharge non-oscillatory. If r is small each of these successive discharges is an oscillation.

Such an unstable circuit gives a continuous series of successive discharges, which are single impulses, as in Fig. 4, or more commonly are oscillations.

If the line conductors A and B in Fig. 4 have appreciable inductance, as is the case with transmission lines, in the charge

of the condenser C_1, after it has been discharged by the arc over P, the voltage e_1 would rise beyond e, approaching $2e$, and the discharge would thus start over P, even if the disruptive strength of this gap is higher than e, provided that it is still below the voltage momentarily reached by the oscillatory charge of the line condenser C_1.

This combination of two transmission line conductors and the ground conductor P, approaching near line A to a distance giving a striking voltage above e, but below the momentarily charging voltage of C_1, then constitutes a circuit which has two permanent conditions, one of stability and one of instability. If the voltage $2e$ is gradually applied, $e_1 = e_2 = e$, the condition is stable, as no discharge occurs over P. If, however, by some means, as a momentary overvoltage, a discharge is once produced over the spark gap P, the unstable condition of the circuit persists in the form of successive and recurrent discharges.

The most interesting class in this group of unstable electric systems is the oscillations resulting sometimes from a change of circuit conditions (switching, change of load, etc.) which continue indefinitely with constant intensity, or which steadily increase in intensity, and may thus be called permanent and cumulative surges, hunting, etc. They may be considered as transients in which the attenuation constant is zero or negative.

In the transient resulting from a change of circuit conditions, the energy which represents the difference of stored energy of the circuit before and after the change of circuit conditions, is dissipated by the energy loss in the circuit. As energy losses always occur, the intensity of a true transient thus must always be a maximum at the beginning, and steadily decrease to zero or to a permanent condition. An oscillation of constant intensity or of increasing intensity thus is possible only by an energy supply to the oscillating system brought about by the oscillation. If this energy supply is equal to the energy dissipation, constancy of the phenomenon results. If the energy supply is greater than the energy dissipation, the oscillation is cumulative, and steadily increases until self-destruction of the system results, or the increasing energy loss becomes equal to the energy supply, and a stationary condition of oscillation results. The mechanism of this energy supply to an oscillating system from a source of energy differing in frequency from that of the oscillation, is still practically unknown, and very little

investigating work has been done to clear up the phenomenon. It is not even generally understood that the phenomenon of a permanent or cumulative line surge involves an energy supply, or energy transformation, of a frequency equal to that of the oscillation.

Possibly the oldest and best known instance of such cumulative oscillations is the hunting of synchronous machines.

Cumulative oscillations between electromagnetic and electrostatic energy have been observed by their destructive effects in high-voltage electric circuits, on transformers and other apparatus, and have been, in a number of instances where their frequency was sufficiently low, recorded by the oscillograph. They obviously are the most dangerous phenomena in high-voltage electric circuits. Relatively little exact knowledge exists of their origin. Usually, if not always, an arc somewhere in the system is instrumental in the energy supply which maintains the oscillation. In some instances, as in wireless telegraphy, they have found industrial application. A systematic theoretical investigation of these cumulative electrical oscillations probably is one of the most important problems before the electrical engineer today.

The general nature of these permanent and cumulative oscillations and their origin by oscillating energy supply, from the transient of a change of circuit condition, is best illustrated by the instance of the hunting of synchronous machines, and this may, therefore, be investigated somewhat more in detail.

Practically all theoretical study of the hunting of synchronous machines has been limited to the calculation of the frequency of the transient oscillation of the synchronous machine, at a change of load, frequency or voltage, at synchronizing, etc. However, this transient oscillation is harmless, and becomes dangerous only if the oscillation ceases to be transient, but becomes permanent and cumulative; and thus the most important problem in the study of hunting is the determination of the cause which converts the transient oscillation into a cumulative one; that is, the determination of the source of the energy, and the mechanism of its transfer to the oscillating system. To design synchronous machines so as to have no or very little tendency to hunting, obviously requires a knowledge of those characteristics of design which are instrumental in the energy transfer to the oscillating system, and thereby cause hunting, so as to avoid them and produce the greatest possible inherent stability.

If, in an induction motor running loaded, at constant speed, the load is suddenly decreased, the torque of the motor being in excess of the reduced load causes an acceleration, and the speed increases. As, in an induction motor, the torque is a function of the speed, the increase of speed decreases the torque, and thereby decreases the increase of speed until that speed is reached at which the motor torque has dropped to equality with the load, and thereupon acceleration and further increase of speed ceases, and the motor continues in operation at the constant higher speed. That is, the induction motor reacts on a decrease of load by an increase of speed, which is gradual and steady without any oscillation.

If, on a synchronous motor running loaded, the load is suddenly decreased, the beginning of the phenomenon is the same as in the induction motor; the excess of motor torque causes an acceleration, that is, an increase of speed. However, in the synchronous motor the torque is not a function of the speed, but in a stable condition, the speed must always be the same, synchronism, and the torque is a function of the relative position of the rotor to the impressed frequency. The increase of speed, due to the excess torque resulting from the decreased load, causes the rotor to run ahead of its previous relative position, and thereby decreases the torque until by means of increased speed, the motor has run ahead from the relative position corresponding to the previous load, to the relative position corresponding to the decreased load. Then the acceleration, and with it the increase of speed, stops. But the speed is higher than in the beginning, that is, is above synchronism, and the rotor continues to run ahead, the torque continues to decrease, is now below that required by the load, and the latter thus exerts a retarding force, decreases the speed, and brings it back to synchronism. But when synchronous speed is reached again the rotor is ahead of its proper position, and thus cannot carry its load, and it begins to slow down, until it is brought back into its proper position. At this position, however, the speed is now below synchronism, and the rotor thus continues to drop back, and the motor torque increases beyond the load, thereby accelerates again to synchronous speed, etc., and in this manner conditions of synchronous speed, with the rotor position behind or ahead of the position corresponding to the load, alternate with conditions of proper relative position of the rotor, but below or above synchronous speed; that is, an oscil-

lation results which usually dies down at a rate depending on the energy losses resulting from the oscillation.

As seen, the characteristic of the synchronous machine is, that readjustment to a change of load requires a change of relative position of the rotor with regard to the impressed frequency without any change of speed, while a change of relative position can be accomplished only by a change of speed, and this results in an over-reaching in position and in speed; that is, in an oscillation.

Due to the energy losses caused by the oscillation, the successive swings decrease in amplitude, and the oscillation dies down. If, however, the torque which brings the rotor back from the position ahead or behind its normal position corresponding to the changed load (excess or deficiency of motor torque and of the torque required by the load) is greater than the torque which opposes the deviation of the rotor from its normal position, each swing tends to exceed the preceding one in amplitude, and if the energy losses are insufficient, the oscillation thus increases in amplitude and becomes cumulative; that is, hunting.

In Fig. 5 is shown diagrammatically, as p, the change of the relative position of the rotor, from p_1, corresponding to the previous load, to p_2, the position further forward corresponding to the decreased load: v then shows the oscillation of speed corresponding to the oscillation of position.

The dotted curve, w_1, then shows the energy losses resulting from the oscillation of speed (hysteresis and eddies in the pole faces, currents in damper windings), that is, the damping power, assumed as proportional to the square of the speed.

If there is no lag of the synchronizing force behind the position displacement, the synchronizing force, that is, the force which tends to bring the rotor back from a position behind or ahead of the position corresponding to the load, would be—or may approximately be assumed as—proportional to the position displacement p, but with reverse sign: positive or accelerating when p is negative or behind the normal position, negative or retarding when p is ahead. The synchronizing power, that is, the power exerted by the machine to return to the normal position, then is derived by multiplying $-p$ by v, and is shown dotted as w_2 in Fig. 5. As seen, it is a double-frequency alternation with zero as average.

The total resultant power or the resulting damping effect

which restored stability, then is the sum of the synchronizing power w_2 and the damping power w_1, and is shown by the dotted curve w. As seen, under the assumption of Fig. 5, in this case a rapid damping occurs.

If the damping winding, which consumes a part or all the power w_1, is inductive—and to a slight extent it always is—the current in the damping winding lags behind the e.m.f. induced in it by the oscillation, that is, lags behind the speed v, and the power w_1, or that part of it which is current times voltage, then ceases to be continuously negative or damping, but contains a

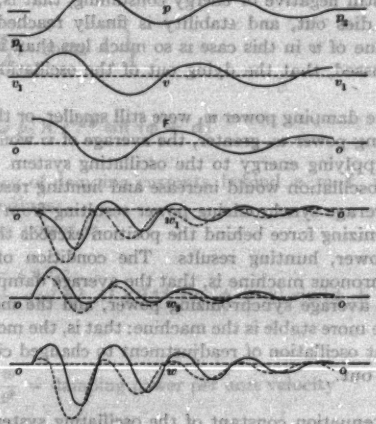


FIG. 5—OSCILLATIONS DUE TO CHANGE OF LOAD

positive period, and its average is greatly reduced, as shown by the drawn curve w_1, in Fig. 5; that is, inductivity of the damper winding is very harmful, and it is essential to design the damper winding as non-inductive as possible to give efficient damping.

With the change of position p, the current, and thus the armature reaction, and with it the magnetic flux of the machine, changes. A flux change cannot be brought about instantly, as it represents energy stored, and as a result the magnetic flux of the machine does not exactly correspond with the position p,

but lags behind it, and with it the synchronizing force F, as shown in Fig. 5, more or less, depending on the design of the machine.

The synchronizing power of the machine, $F v$, in the case of a lagging synchronizing force F, is shown by the drawn curve w_2. As seen, the positive ranges of the oscillation are greater than the negative ones; that is, the average of the oscillating synchronizing power is positive, supplying energy to the oscillating system, which energy tends to increase the amplitude of the oscillation; in other words, tends to produce cumulative hunting.

The total resulting power, $w = w_1 + w_2$, under these conditions, is shown by the drawn curve w, in Fig. 5. As seen, its average is still negative or energy consuming, that is, the oscillation still dies out, and stability is finally reached, but the average value of w in this case is so much less than in the case above discussed, that the dying out of the oscillation is much slower.

If now the damping power w_1 were still smaller, or the average synchronizing power w_2 greater, the average of w would become positive, supplying energy to the oscillating system. In other words, the oscillation would increase and hunting result. That is, if the average synchronizing power resulting from the lag of the synchronizing force behind the position exceeds the average damping power, hunting results. The condition of stability of the synchronous machine is, that the average damping power exceeds the average synchronizing power, and the more this is the case, the more stable is the machine; that is, the more rapidly the transient oscillation of readjustment to changed circuit conditions dies out.

Or, if

a = attenuation constant of the oscillating system,

$a < 0$ gives cumulative oscillation or hunting;

$a > 0$ gives stability.

Counting the time t from the moment of maximum backward position of the rotor, that is, the moment at which the load on the machine is decreased, and assuming sinusoidal variation, and denoting

$$\phi = 2 \pi f t = \omega t \tag{1}$$

where

$$f = \text{frequency of the oscillation,} \tag{2}$$

the relative position of the rotor may then be represented by

$$p = - p_0 \cdot \epsilon^{-a\phi} \cos \phi$$

where

$$p_0 = p_2 - p_1 = \text{position difference of rotor resulting from change of load,} \tag{3}$$

$$a = \text{attenuation constant of oscillation.} \tag{4}$$

The velocity difference from that of uniform rotation then is

$$v = \frac{dp}{dt} = \omega \frac{dp}{d\phi} = \omega\, p_0\, \epsilon^{-a\phi} (\sin \phi + a \cos \phi) \tag{5}$$

Let

$$a = \tan \alpha; \quad 1 + a^2 = A^2 \tag{6}$$

hence

$$\sin \alpha = \frac{a}{A}; \quad \cos \alpha = \frac{1}{A} \tag{7}$$

it is

$$v = \omega\, p_0\, A\, \epsilon^{-a\phi} \sin (\phi + \alpha) \tag{8}$$

Let

γ = lag of damping currents behind e. m. f. induced in damper windings; (9)

the damping power is

$$\begin{aligned} w_1 &= - c\, v\, v_r \\ &= - c\, \omega^2\, p_0^2\, A^2\, \epsilon^{-2a\phi} \sin (\phi + \alpha) \sin (\phi + \alpha - \gamma) \end{aligned} \tag{10}$$

where

$$c = \frac{w}{v^2} = \text{damping power per unit velocity} \tag{11}$$

Let

β = lag of synchronizing force behind position displacement p, and (12)

$$\beta = \omega\, t_0 \tag{13}$$

where

$$t_0 = \text{time lag of synchronizing force.} \tag{14}$$

The synchronizing force then is

$$F = b\, p_0\, \epsilon^{-a\phi} \cos (\phi - \beta) \tag{15}$$

where

$$b = \frac{F_0}{p_0} = \text{ratio of synchronizing force to position displacement, or specific synchronizing force.} \tag{16}$$

The synchronizing power then is

$$w_2 = Fv = b\,\omega\,p_0^2\,A\,\epsilon^{-2a\phi}\,\sin(\phi+\alpha)\cos(\phi-\beta) \tag{17}$$

The oscillating mechanical power is

$$w = \frac{d}{dt}\frac{mv^2}{2} = m\,\omega\,v\,\frac{dv}{d\phi}$$

$$= m\,\omega^3\,p_0^2\,A^2\,\epsilon^{-2a\phi}\sin(\phi+\alpha)\{\cos(\phi+\alpha) - a\sin(\phi+\alpha)\} \tag{18}$$

where

m = moving mass reduced to the radius, on which p is measured. (19)

It is, however,

$$w_1 + w_2 - w = 0. \tag{20}$$

Hence, substituting (10), (17), (18) into (20) and cancelling,

$$b\cos(\phi-\beta) - c\,\omega\,A\sin(\phi+\alpha-\gamma) - m\,\omega^3\,A\cos(\phi+\alpha) + m\,\omega^2\,A\,a\sin(\phi+\alpha) = 0 \tag{21}$$

This gives as the coefficients of $\cos\phi$ and $\sin\phi$ the equations

$$\left.\begin{aligned} b\cos\beta - c\,\omega\,A\sin(\alpha-\gamma) - m\,\omega^2 A\cos\alpha + m\,\omega^2 A\,a\sin\alpha = 0 \\ b\sin\beta - c\,\omega\,A\cos(\alpha-\gamma) + m\,\omega^2 A\sin\alpha + m\,\omega^2 A\,a\cos\alpha = 0 \end{aligned}\right\} \tag{22}$$

Substituting (6) and (7) and approximating from (13), for α as a small quantity,

$$\cos\beta = 1;\quad \sin\beta = \omega\,t_0 \tag{23}$$

gives

$$\left.\begin{aligned} b - c\,\omega\,(a\cos\gamma - \sin\gamma) - m\,\omega^2(1-a^2) &= 0 \\ bt_0 - c\,(\cos\gamma + a\sin\gamma) + 2m\,\omega\,a &= 0 \end{aligned}\right\} \tag{24}$$

This gives the values, neglecting smaller quantities,

$$a = \frac{c\cos\gamma - b\,t_0}{\sqrt{4\,mb - c^2\cos 2\gamma + b^2 t_0^2}} \tag{25}$$

$$\omega = \frac{1}{2\,m}\{\sqrt{4\,mb - c^2\cos 2\gamma + b^2 t_0^2} + c\sin\gamma\} \tag{26}$$

$$f = \frac{\omega}{2\pi} \tag{27}$$

These equations (25) and (26) apply only for small values of a, but become inaccurate for larger values of a, that is, very rapid damping. However, the latter case is of lesser importance.

$$a = 0 \text{ gives}$$
$$b\, t_0 = c \cos \gamma$$

Hence

$$\left.\begin{aligned} c &> \frac{b\, t_0}{\cos \gamma} \\ \text{or} \qquad t_0 &> \frac{c \cos \gamma}{b} \end{aligned}\right\} \qquad (28)$$

is the condition of stability of the synchronous machine.

If

$$t_0 = 0$$
$$\gamma = 0$$

then

$$a = \frac{c}{\sqrt{4\, mb - c^2}}$$

$$\omega = \frac{\sqrt{4\, mb - c^2}}{2m}$$

and, if, also,

$$c = 0$$

$$\omega = \sqrt{\frac{b}{m}}$$

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, November 14, 1913.

Copyright 1913 By A. I. E. E.

DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS

BY ALFRED E. WALLER

Dynamo lighting equipments on motor cars are required to maintain at all times a supply of electric energy sufficient for proper road lighting. It is therefore natural, in the design of such apparatus, to decide first what may be accepted as a satisfactory set of lamps for motor car use. When this point has been determined, the capacity of dynamo, battery, and auxiliary apparatus may be readily deduced.

The choice of lamps is influenced by a great many considerations, and among these is the variable element of individual preference. Some drivers prefer to have a good deal of light near the car, others insist upon lamps which will project the light a considerable distance ahead, and leave objects close at hand in comparative darkness. Many arguments are offered in favor of each type, and, in order to have his product meet with general favor, a lamp designer must take both extremes into account.

A great deal of interesting experimental work has been done with headlights of both American and foreign design, in order to determine the characteristics of the most suitable lamp and reflector.

As a result the 21-c.p. six-volt tungsten lamp has been adopted for use with a parabolic reflector measuring 10 in. (25.4 cm.) across the opening.

This choice was governed by several considerations. In the first place it was shown that with lamps of this description a road 50 ft. (15.2 m.) wide could be perfectly lighted for a distance of at least 1000 ft. (304.8 m.) in advance of the car. Objects on the road could be distinguished practically as far away as

would be possible in daylight, and always in ample time to stop or turn aside as the case rendered necessary.

In the second place, 10-in. (25.4 cm.) reflectors were used because they did not necessitate extremely large headlights, which, beside being costly, would detract from the appearance of a motor car. The importance of having lamps properly focused was brought out in these experiments. For the best results the lamp filament must be located exactly at the focus of the parabolic reflector, and the reflector should be so designed that the focus is well back from the opening. A comparatively deep reflector makes the angle of the direct rays not intercepted by it, rather small, consequently a greater proportion of the total candle power may be projected in a useful direction. The effect is particularly good when the lights are placed at least three ft. (0.9 m.) from the ground. At this height the shadows caused by slight ridges and undulations in the road are not so apparent as when the lights are placed lower.

The 10-in. (2.54 cm.) parabolic reflector adopted, measures about 5½ in. (14 cm.) in depth. This reflector has a focus of 1⅛ in. (2.85 cm.) and, when properly focused, a 21-c.p. lamp gives ample light on the road near the car and at the same time has very good distance qualities.

Very deep reflectors both of the eight-in. (20.3 cm.) and 10-in. (25.4 cm.) diameter sizes were tried, but it was found that these did not give satisfactory lighting near the car.

Twenty-four c.p. lamps were tried out in the 10-in. (25.4 cm.) reflector, but the difference in illumination was scarcely noticeable, and was more than offset by the fact that the 24-c.p. lamps required 14 per cent more current than the 21-c.p.

The side and rear lights, which are used only as signal lights, and have little value for road lighting purposes, were equipped with four-c.p. and two-c.p. lamps respectively. Lights of lower candle power than this would have been ample for the purpose, but in the smaller sizes of lamps the filaments were found to be too frail to give reliable service under the conditions of severe vibration encountered on a motor car.

Considering, therefore, that a proper equipment consists of a pair of 21-c.p. headlights, a pair of four-c.p. side lights, and a two-c.p. rear light, we find the current taken by these lamps to be seven amperes, 1.7 amperes and 0.6 amperes respectively, making a total load of 9.3 amperes at 6 volts. In addition to this equipment we find on the average car an electric horn and

a speedometer light, but as these devices are used only intermittently, their current is not an important factor in determining the maximum dynamo capacity which will be required.

Allowing for the intermittent use of the speedometer light and electric horn, it is evident from the figures quoted above, that an adequate lighting dynamo must have an output of 10 amperes, in order to maintain at all times a sufficient supply of energy. Further, as the dynamo is available as a source of energy only when the motor car engine is running, a battery must be provided to furnish current when the engine is at rest. A three-cell lead battery has been universally adopted for use with 6-volt lights, and the dynamo must therefore be capable of furnishing 10 amperes at a voltage sufficient to charge a battery of this type.

Our next consideration is the car speed at which the full load output of the dynamo must be delivered. Much of the mileage covered by the average motorist is traversed at a speed of not more than 18 miles per hour, and if we are to reserve the storage battery for use when the motor car engine is not running, our dynamo must be so geared that it will carry the entire light load when the car is traveling at this speed or above. If the speed falls below say 18 miles per hour, more or less current will be drawn from the battery, as the dynamo will not be generating its full capacity. A great deal of night driving at slow speed with all lights on, would in time run down the storage battery, but it is found in practise that little slow-speed running is done with all lights on. In the city, where this condition does prevail to a large extent, the headlights are not as a rule in use, and the load taken by the remainder of the equipment is readily supplied by the dynamo. Further, if the car is used in the day time at all, the charge accumulated by this running serves to keep the battery always charged and in perfect condition. If cars are left standing, the headlights are of course turned off and the 2.3 ampere load represented by the side and rear lights may be carried for some time upon a proper battery.

The ideal electric lighting system is entirely automatic. Means must be provided for connecting the dynamo to the battery when speed proper for charging has been reached, and for disconnecting the dynamo from the battery when the speed is reduced to a point where a reversal of current is about to take place. This is a feature which is present in all properly designed lighting systems.

In some systems now on the market, the connecting and disconnecting from the battery is accomplished by a centrifugally operated switch. The dynamo speed which corresponds to a correct voltage for charging is predetermined, and the centrifugal device is set to close the circuit at this time, and to open it as soon as the speed is reduced below the safe point. In most cases, however, the operation is accomplished by means of an electromagnetic switch. This switch or relay, as commonly constructed, has two windings, one of high resistance which is permanently connected across the armature terminals. The relay is set so that it closes the circuit between the dynamo and the battery, when energized by a potential sufficient for charging the battery, and opens the circuit when the dynamo voltage is reduced below this point. As a precautionary measure, a series winding is placed upon the relay with the shunt winding. This series winding reenforces the shunt winding while charging is going on, but bucks it upon reversal of current, thus tending to produce complete demagnetization of the relay.

One of the most important functions of the automatic lighting system is the control of the dynamo output at the very high speeds reached by motor car engines. It will be readily understood that if a dynamo is arranged so that it is driven at say 1000 rev. per min. at a car speed of 20 miles (32 km.) per hour, and is delivering its full output at this speed, when the car speed has been increased to 40 miles (64.3 km.) or even 60 miles (96.5 km.) per hour, a dynamo not properly protected will be forced to generate current far in excess of its rated capacity and a burn-out will inevitably result. No matter what type of dynamo is used, there must be some means of compensating for the current fluctuations which occur with speed changes.

As in the case of the automatic switch for connecting to the battery, the more difficult problem of controlling dynamo output has been accomplished by means of both mechanical and electrical devices. It is my intention in this paper merely to describe a number of regulators which are now widely used, without commenting either favorably or unfavorably upon their respective merits.

Considering first the mechanical types of control, we have slipping clutches of different designs. For example, one manufacturer uses a clutch composed of two members, one of which is rigidly attached to the dynamo shaft, and the other to some convenient drive shaft. The clutch members are held together

by spring pressure, and, as the speed of the driving member increases, this spring pressure is neutralized by means of centrifugal governors, which oppose the spring tension, and allow slippage between the clutch members, the amount of slippage depending upon the speed of the driving member. This allows the dynamo to be driven at a substantially constant speed, regardless of that of the motor car.

The regulator adopted by another manufacturer has in it a centrifugal governor which turns at the same speed as the dynamo, and moves a small contact arm over a number of steps of resistance inserted in the field circuit of the dynamo. The greater the dynamo speed, the more resistance is inserted with the field, so that a substantially constant output is obtained.

There is a much larger number of electrical devices for this purpose. One of the earliest consisted of a resistance made of small carbon disks arranged in a tube and connected in series with the dynamo field winding. The disks are normally pressed very tightly together by a spring, and in this condition have a low electrical resistance. The device is so arranged that the armature current of the dynamo passes through a series coil, which is arranged to pull directly against the spring which compresses the carbon disks. Consequently when excessive charging rates are reached, the pull of the series coil tends to neutralize the spring pressure upon the carbon disks, and the resistance of the field circuit is increased by the release of pressure.

One method which is much used with the permanent field type of dynamo is to design a machine with high armature reactions, and to depend upon these to prevent excessive generation of current. Compound windings have been successfully used with both bipolar and multipolar dynamos for this work, in spite of the very great range of speed encountered.

Other manufacturers have used double field windings, one portion arranged to opppose the flux generated by the other portion. These opposing or bucking coils are thrown into play at the proper moment by a series relay inserted in the armature circuit.

One magneto type dynamo manufactured has a permanent field with auxiliary electromagnetic field windings, which are disconnected when a certain current has been reached. If the speed is increased beyond this point, the auxiliary electromagnetic fields are again brought into play and are energized so as to oppose the flux of the permanent field. This gives a very wide range of regulation.

In several cases, modifications of the controls described above have been used by regulating the dynamo for a certain maximum voltage instead of maximum current.

In another lighting system, regulation is accomplished by the introduction of a coil of iron wire in the armature circuit. This coil has the property of increasing resistance very slowly, until a certain critical current is reached, and then increasing at a very rapid rate to several times its original resistance. The terminals of a bucking field coil are connected across this series coil of iron wire, which is so designed that the critical point where its resistance increases rapidly, is reached when the maximum dynamo current is being generated. Normally the potential difference applied to the terminals of the bucking coil is negligible, but when the iron wire has become sufficiently heated, this potential difference becomes sufficient to generate a considerable flux in the bucking coil, and to reduce materially the output of the dynamo.

Among the devices designed to secure constant dynamo output at varying speeds, are several foreign inventions. In one of these a bipolar shunt-wound dynamo is arranged with a pair of auxiliary poles placed between the main poles of the machine. The auxiliary poles are not wound, but are excited by the cross magnetization caused by the working current in the dynamo armature. Two brushes are placed in the neutral position relative to the main poles, and are sufficiently wide to short-circuit several armature coils during the period of commutation. When the armature is revolved the dynamo behaves as any ordinary shunt-wound machine, except that the load current in the armature conductors, by virtue of its cross-magnetizing ampere-turns, sets up a flux in the auxiliary unwound poles, provided to receive it. The armature coils short-circuited by the brushes cut this cross flux and consequently have a short-circuit current induced in them, which is proportional to the cross flux and to the speed of rotation. This short-circuit current acts in such a direction as to demagnetize the main wound poles. In this manner the voltage of the dynamo is regulated so as to compensate for speed changes and also for load changes.

One foreign manufacturer has designed a distributing panel, in which each circuit on the car has a properly proportioned coil of resistance wire in series with it. This wire is of such gage and length that it permits a certain amount of current

to flow in the circuit, this being predetermined, and increases in resistance to eight or ten times its nominal value when this current value is exceeded, thus protecting the lamps against burn-out.

In a well-known French design a bipolar dynamo is used, with two windings on each pole, the pairs being wound to produce magnetization in the same direction. One side of each of the four coils is connected to the negative brush of the dynamo, and the four remaining terminals are connected to the positive brush, through four small breakers arranged concentrically around the dynamo shaft. These breakers are opened in succession by a cam on the end of the dynamo shaft, and only one breaker is opened at a time. At low speeds the effect produced by opening momentarily one of the four field coils and closing it again before opening another, is negligible, but as the speed is increased the interruptions become so rapid that the dynamo field does not have time to build up to its full intensity, and constant output may be secured from the dynamo over a wide speed range.

In the particular lighting system under consideration a plain shunt-wound dynamo was adopted as being the simplest and most reliable type, and a system of control was developed which gives perfectly satisfactory regulation. The necessary regulation is secured by means of a single step of resistance inserted in series with the dynamo field. This resistance, which is of such a value that it will limit the dynamo output to its predetermined maximum at the highest car speed obtainable, is normally short-circuited, but the short circuit is removed from the resistance when the maximum charging current has been reached. This is accomplished by means of a relay, only one winding of which carries the armature current. In practise, the short circuit is removed from the resistance in series with the dynamo field when a current of 10.1 amperes has been reached, and when this resistance is thus inserted in the field circuit, the dynamo output immediately falls off. When the current is reduced to 9.9 amperes, the resistance is once more short-circuited, and, as the interval of time required for this change in current is very short, an extremely rapid vibration of the relay contact is set up, and a substantially constant current is obtained over a wide range of speed.

In the early experimenting, a relay of the familiar telegraph type was used, but lengthy experiments led to the adoption

of a modified type in which the trunnions or pivots are replaced by a flexible phosphor-bronze hinge of suitable gage and width. This construction is found to be highly satisfactory, and is not affected by vibration.

There are a number of other systems of control which are quite as efficient and well known as these I have mentioned, and a great deal of time might be devoted to their discussion and comparison. It is necessary at this time, however, to consider the initial speed at which a dynamo should be designed to give its full output. This is an important consideration, and is so closely related to the construction of the motor car engine with which the system is to be used, that the general arrangement of the engine must be carefully taken into account.

It is well known that the size, weight and cost of a dynamo of any particular type, depends not only upon the watt output, but also upon the speed at which this output is delivered. Consider as an example the shunt-wound dynamo; one which will deliver 7.5 volts and 10 amperes at 1500 rev. per min., costs 30 per cent less than one which will deliver the same output at 1000 rev. per min., and less than half as much as one designed for a speed of 500 rev. per min. The weights of the respective machines are in approximately the same ratio as their cost.

A shunt-wound dynamo designed for the stated output at approximately 1000 rev. per min. weighs about 21 lb. (9.5 kg.) and can be made approximately 8 in. (20.3 cm.) long by 5⅝ in. (13.2 cm.) high by 4¾ in. (12 cm.) wide. If it is required to secure the same output at 500 rev. per min. the weight must be increased to approximately 35 lb. (15.8 kg.) and the dimensions become 9¼ in. (23.5 cm.) by 7½ in. (18 cm.) by 4¾ in. (12 cm.) approximately. On the average four-cylinder motor car, a 1000-revolution dynamo is run at about twice engine speed for the best results, and the 500-revolution dynamo should be run at engine speed.

Bearing these facts in mind, the selection of a dynamo for any particular automobile engine becomes a matter of judgment and must be largely governed by the structure and arrangement of the engine itself. Speaking broadly, it will be found that when a 500-rev. per min. dynamo may be readily coupled to a shaft which runs at engine speed, its extra weight and cost are justified by the fact that it renders sprockets and chain or gears, and their care, unnecessary. On motors where an installation of this type entails the extension of a shaft

not readily accessible, or the use of a countershaft or an idler gear or some other device for bringing the direct drive into a convenient location, a chain-driven dynamo geared to run at twice engine speed may be used to advantage.

Where a geared dynamo is necessary, the shunt-wound machine designed to deliver its output at 1000 rev. per min. and driven at approximately twice engine speed, appears to be the most advantageous design in weight, cost and size. Such a dynamo when driven at twice engine speed on a car with 36-in. (0.9 m.) rear wheels, geared 3½ to 1 on the back axle, will start charging the battery at from six to seven miles (9.6 to 11.2 km.) per hour, and will deliver its full output of 10 amperes at about 15 miles (24.1 km.) per hour. The same dynamo on a car geared 3 to 1 with 36 in. (0.9 m.) rear wheels, would begin to charge the battery at approximately 9 miles (14.4 km.) per hour, and will balance the lamp load at approximately 18 miles (28.9 km.) per hour. A machine of this type has distinct points of advantage over a dynamo designed to deliver its output at either a higher or a lower speed.

Considering first a higher speed dynamo, let us assume a rated speed of 1500 rev. per min. for full output. This dynamo is smaller, lighter and cheaper than a dynamo designed for 1000 rev. per min., but must be driven at approximately three times engine speed. In practise if a ⅜-in. (9.5 mm.) pitch silent chain is used, the driven and driving sprockets will have 15 and 45 teeth respectively. This means a chain speed of 2250 ft. (685.8 m.) per minute at 45 miles (72.4 km.) per hour of the car and 3000 ft. (914.4 m.) per minute at 60 miles (96.5 km.) per hour. These speeds are too high for best results and cause rapid wear of the chain. It should be noted also that the chain is likely to become noisy when driven at this speed.

On the other hand, a dynamo driven at less than twice engine speed, in order to secure lower chain speed, and less wear on the bearings, is not an advantageous arrangement. The cost and weight of the dynamo are immediately increased, without the elimination of sprockets.

It becomes evident, therefore, that if the chain speed reached by the drive of the 1000-rev. per min. dynamo is not excessive, it has a decided advantage over either of the types just mentioned. Investigation shows that in practise, sprockets of 30 and 15 teeth would be used with ⅜-in. (9.5 mm.) pitch silent chain, and at 45 miles (72.4 km.) per hour the chain speed would

be 1500 ft. (457.2 m.) per minute, and at 60 miles (96.5 km.) per hour it would run 2000 ft. (609.6 m.) per minute. These speeds are not excessive and are within the limits of the speed at which a chain may be used with best efficiency.

The problem of driving dynamos on different types of motor car engines is capable of many solutions. In some cases it is possible to secure a direct drive at engine speed, through an Oldham coupling, and this is an instance in which the low-speed dynamo may be used to great advantage. In many cases it is possible to extend the pump shaft back through the pump casing, and to obtain a direct connection in this manner. In other instances it has been possible to move the magneto and to install in the place formerly occupied by it a dynamo with a double-end shaft, to which the magneto is afterwards connected by means of an Oldham coupling, and the two units driven in tandem fashion. This arrangement on a six-cylinder car requires a dynamo wound to deliver its output at 1½ times engine speed, that is, about 750 rev. per min.

With the 1000-rev. per min. dynamo, drive may be secured by means of a sprocket installed on the pump or magneto shaft, a sprocket on an extended half-time shaft, or one fastened to the crank shaft directly back of the clutch which engages the starting handle. In other installations it is possible to drive by a gear, meshing with one of the timing gears, or with one of those in the transmission. Either of these last methods make a very satisfactory installation where they can be used, as the gears, encased and running in oil, are almost absolutely noiseless.

All of these methods and numerous others have been tried out and shown to be entirely satisfactory, both as regards noiseless operation and life.

The remaining points to be considered are the size and capacity of battery to be used, and the method of wiring.

In order to meet satisfactorily the severe conditions to which it is apt to be subjected, the battery must have plates sufficiently large to stand charging at the maximum dynamo output for an indefinite time, without deterioration. This condition would be imposed upon it by an automobile owner who drives only in the day time. It should have sufficient capacity to maintain all lights on the car for six hours, and to carry the side and rear lights only, for from 20 to 24 hours, without receiving any charge.

Exhaustive experiments have demonstrated that a battery with 160 sq. in. (852.3 sq. cm.) or more of positive plate surface

and 100 sq. in. (645.2 sq. cm.) of negative plate surface, is capable of standing a 10-ampere charging rate for very long periods, even when no current is taken from it. It is unquestionably possible to damage a battery of the above size by charging at a 10-ampere rate, if carried on indefinitely on a test bench. The condition of motor car service, however, tend to offset the main causes of deterioration which become noticeable when the batteries are charged at high rates. In the first place a battery charged continuously at a high rate becomes overheated, and this heat softens the plates to such an extent that they are readily disintegrated. Another cause of decay is the formation of large bubbles of gas on the negative plates, which, when they finally break away from the plates, take with them particles of active material, especially when this has become softened due to heating.

The chance of overheating a battery due to continuous high charging rates, becomes rather small when we consider that it is seldom, in practise, that a battery is charged continuously at the maximum rate for more than a few hours at a time. It is seldom indeed that a dynamo in motor car service delivers its full output for several hours at a time without intermission, because automobiles are rarely driven at a continuous speed of 18 miles (28.9 km.) per hour or above for long intervals. In addition to the frequent slowing down of the motor car engine, due to coasting down hill, or turning corners, there are often periods when it is not running or is running slowly, so that the dynamo does not generate its maximum current. It has been proved in practise that in the average installation no appreciable heating takes place, and that even the drivers who maintain the highest average speed never raise their batteries to an excessive temperature. Referring to the second cause for deterioration, it will be evident that the vibration always present in motor car service, makes it practically impossible to form large bubbles upon the battery plates. The jolting of the automobile becomes practically a substitute for the mechanical agitator which is used in many large stationary battery plants.

A battery installed on the average motor car is operating under ideal conditions, as it is either charging or discharging nearly all the time. If the plate surface mentioned above is used, the 9½-ampere load represented by the total light equipment may be carried for approximately 3¼ hours, while the side and rear lights may be kept bright for at least 24 hours. It will be ap-

parent that the 3¼-hour limit for the length of time during which the battery will take care of the entire load, is hardly long enough, so that a battery used in a motor car equipment should have approximately double the capacity given, or approximately 80 ampere-hours. In a very large number of lighting systems now operating successfully, standard makes of batteries rated at 80 ampere-hours with a 10-ampere discharge rate, are proving entirely adequate. A battery of this type has considerably more than the necessary plate area to stand the 10-ampere charging rate indefinitely, and will carry all lamps for at least six hours, a longer time than would be ordinarily required.

The remaining point now to be considered is the method of wiring, and type of wire used. In many of the first lighting systems, the proposition of a ground return for all fixtures was pointed out, but in practically all instances the system of running two wires to each lamp and fixture has been adopted. Ground returns in many cases brought about ignition complications, and the system of two wires has a decided advantage in that one conductor may be grounded accidentally without interfering with the lights. On the ground return system an abrasion or injury to the current-carrying wire is apt to put the entire system out of operation. In a recommendation to a special advisory committee of the Society of Automobile Engineers, Mr. Leonard Kebler, a member of the Society, proposed that for motor car installation, a cable be used capable of standing a test of 12 hours immersion in oil, 12 hours immersion in gasolene, and 12 hours immersion in water, and then stand 500 volts applied between the two conductors without a breakdown. Wire of this type has been used extensively by several manufacturers and has been found to give excellent results.

The insulation of wire for motor car use, should be composed preferably of some material which is not affected by oil or gasolene, and is not softened by ordinary temperatures. Where rubber is used it should be protected against oil and gasolene to prevent the possibility of grounds and short circuits.

In concluding, it may be said of the lighting system wiring that the manufacturer should, if possible, cut all wires to length and make all connections before shipment. Experience proves that the highest satisfaction with motor car lighting equipments may be obtained only when the wiring is done by skilled operators. Consequently, a lighting system designed

in such a manner that it may be purchased for any particular make or model of car, with all wires cut to length and fitted with proper plugs, all connections made to panels, switches, etc., possesses distinct advantages. The work of installation is reduced practically to fastening the switch, controlling panel, battery, and dynamo to the car. It has been found possible to arrange lighting systems in such a manner that the only connections which need to be made by the user, are those between the system of wiring and the dynamo, and also to the battery terminals.

By arranging the dynamo connections with different sizes of binding posts, so that the wires cannot be put on in wrong order, and treating the battery binding posts in the same manner, the chances of trouble due to improper wiring are reduced to a minimum, and satisfaction is secured from the point of view both of the manufacturer and the automobile owner.

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, November 14, 1913.

Copyright, 1913. By A. I. E. E.

ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS

BY ALEXANDER CHURCHWARD

For supplying current for starting and lighting the modern motor car a constant-speed dynamo has many advantages over every other type of dynamo, viz:

1. It charges a battery as it should be charged; that is, with a comparatively large current when the battery is low and empty, tapering off to a small charging rate when the battery is full and at the gassing point.

2. Its comparatively low speed, even at high car speed, means long life, small wear and maintenance, and—what is most necessary—reliability.

3. Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by a "bucking series" coil or by regulation of the field current.

In other words, the loss due to the friction and slipping of the clutch is less than the core loss of variable speed machines running at high speeds.

4. Its ability to run the lights, even when the battery is disconnected—accidentally or otherwise.

5. It can be geared to cut in at very low car speeds, as the speed of the dynamo armature never exceeds a safe, predetermined limit.

Experience has shown in the past four years that it is far better to charge a battery at a moderate rate whenever the car attains a speed of 8 miles (12.8 km.) per hour than to charge at a very low rate at 10 miles (16 km.) per hour and gradually increase the charging rate as the car speed rises. A variable-speed,

constant-current dynamo, giving enough current to take care of the lights, invariably over-charges the battery on long daylight runs of some hours' duration. The user may not have to renew the battery frequently, but the direct effect is to boil the solution out of the battery, and at some time when current is

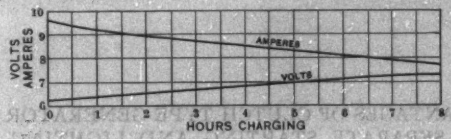


FIG. 1—TAPER CHARGE EFFECT OF CONSTANT-SPEED DYNAMO.

needed the battery fails because of a lack of electrolyte; or whatever electrolyte is left is so concentrated as to injure the plates.

This is not the case with a constant-speed machine, which gives neither constant current nor constant potential. When the

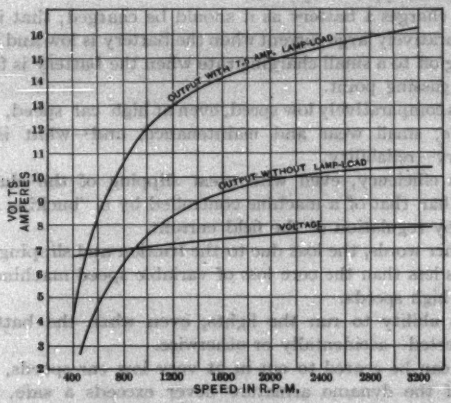


FIG. 2—OVERCHARGING EFFECT OF VARIABLE-SPEED DYNAMO.

battery is low it will give a comparatively heavy current, say 10 amperes, which will taper off to four or five amperes as the battery becomes fully charged, the voltage rising from approximately 6.5 volts to 7.75 volts when battery of three cells is fully charged. Fig. 1 shows the tapering charge effect; while Fig. 2

shows the over-charge effect of a variable-speed machine; the battery voltage rising to over eight volts, from which of course the lamps and battery would both suffer.

The constant-speed machine can be compounded so that when lamps are turned on it will maintain a constant potential of a proper value at the lamps.

The advantages of the compound-wound, constant-speed dynamo, that is compound-wound for lighting and shunt-wound

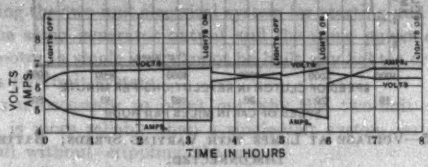


FIG. 3—TAPER CHARGE AND COMPOUND CHARACTERISTICS OF DYNAMO

for charging battery, must be at once apparent to even the most casual observer:

1. Proper rate of charging, dependent upon condition of battery.

2. Tapering charge as battery is filled up.

3. Sufficient current to light the lamps and to put a small charge into the battery. Take for example a system equipped with lamps that call for a total of eight amperes at six volts:

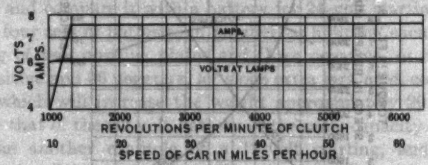


FIG. 4—VOLTAGE AT LAMPS AT DIFFERENT SPEEDS.

The charging rate to the battery will vary from 10 amperes when the battery is cold and low to five amperes when the battery is warm and charged.

If we now turn on the lamps, which are connected through the series or compound winding, the machine will give nine amperes, the battery receiving at first one ampere, while its counter electromotive force is high from just coming off charge; but it will gradually settle until the dynamo is giving 10 amperes,

eight of which go to the lights and two to the battery. This will keep the battery voltage at approximately 6.6 volts. There will be a drop in the wiring, instruments, etc., of from 0.4 to 0.5 of a volt, so that the voltage at the six-volt lamps will be main-

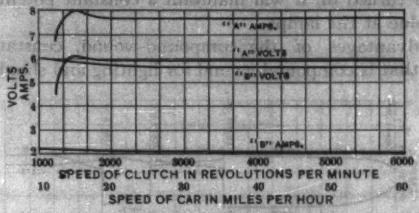


FIG. 5—VOLTAGE AT LAMPS WITH VARYING SPEEDS; BATTERY DISCONNECTED.

tained within 0.1 of a volt. Figs. 3, 4 and 5 show how the potential is maintained at the lamps.

Mention has been made, above, only of a lamp potential of six volts, corresponding to three cells of lead battery, as we have

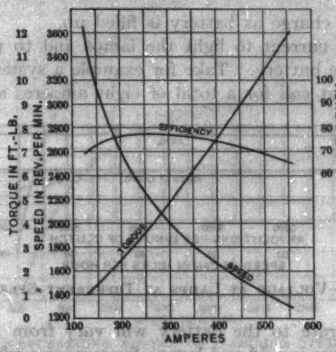


FIG. 6—CHARACTERISTICS OF SIX-VOLT SERIES-WOUND STARTING MOTORS.

found that it is possible to design our starting system so that we have a more efficient motor at six volts—the standard voltage for ignition—than most of the other systems using 18 to 24 volts.

Experience in designing electric automobile motors during the past 15 years has demonstrated that to get the most out of a battery, regardless of the number of cells, the best design which can be employed is a series motor with a steep torque characteristic (see Fig. 6).

A shunt-wound dynamo at constant speed being the best for charging batteries, and having characteristics exactly opposite to those of a series motor, explains the reason for our adopting the two-unit electrical system for starting and lighting. For the same generator output and the same power delivered as a motor, a single unit cannot be built any lighter or cheaper than a two-unit system.

It is unnecessary to point out why the two-unit electrical sytem is more reliable than a single-unit system, as one unit can fail without crippling the car.

In regard to weight of different voltage systems, the single unit system almost always calls for a larger number of cells in series for starting, and in multiple for lighting. The battery capacity is invariably fixed by the lighting conditions, and not by the starting conditions; and the amount of power required for starting is very small compared with that required for lighting. In fact, it is only a surface discharge. For instance: Take a six-volt battery of 80-ampere-hour capacity, that is, eight amperes for 10 hours. It will require 11 plates per cell, five positive and six negative, or 15 positive and 18 negative total; and compare it with a battery for 24-volt starting system using four sets of batteries in parallel for lighting, each cell consisting of two positive plates and three negative, or a total of 24 positive and 36 negative, let alone extra jars, acid, connectors, etc., which will increase the weight approximately 20 per cent above that of the six-volt battery of the same capacity.

Take another example of a 12-volt starting, and 12-volt, three-wire lighting system: The same battery capacity will be needed, only in this case 40 ampere-hours at 12 volts; therefore, there will be three extra positive and six extra negative plates, or one per cell; also extra acid, extra connectors, etc.; and the increase of weight will be approximately 10 per cent, or as much as the weight of the generator unit itself.

Therefore, the writer maintains that a six-volt double unit system properly designed and built will weigh less and be more efficient per pound than any system designed for a higher voltage.

Precautions in charging vehicle automobile motors during the past 15 years has demonstrated that we are the most ideal battery, regardless of the number of cells, the unit of charge which can be employed has never been with a lamp corrupt characteristic (see fig. 6).

A third sound charging at constant speed being the best for charging batteries, and having characteristics exactly opposite to the unit a series motor, requires the reason for our adopting the two-unit electrical system for starting and lighting. For the same accumulator output and the same power delivered as a motor, a single unit cannot be built any lighter or cheaper than a two-unit system.

It is unnecessary, as points out why the two-unit electrical system is more reliable than a single-unit system, as one unit can fail without crippling the car.

In regard to weight of efficient voltage systems, the single unit system about always will have lower voltage of cells in series for starting, and is suitable for lighting. The battery capacity is invariably fixed by the lighting conditions, and not by the starting conditions, and the amount of power required in starting is very small compared with that required for lighting. In fact, it is only in starting, definitely. For instance, Take a 12-volt battery of 80-ampere-hour capacity, that is, eight amperes for 10 hours. It will require 11 plates per cell, five positive and six negative, or 15 positive and 18 negative total; and compare it with a battery for 24-volt starting system using four sets of batteries in parallel for lighting, each cell consisting of two positive plates and three negatives, or a total of 24 positive and 30 negative, let alone extra lug, acid, connectors, etc., which will increase the weight approximately 20 per cent above that of the 12-volt battery of the same capacity.

Take another example of a 12-volt starting, and 12-volt three-wire lighting system. The same battery capacity will be needed, only in this case 40 ampere hours at 12 volts; therefore, there will be three extra positive and six extra negative plates, or one per cell, also extra acid, extra connectors, etc., and the increase of weight will be approximately 10 per cent, or as much as the weight of the generator and shaft.

If for instance the motor requires the 24-volt system, both equally adequate and have well weight for and be more efficient, and there are certain designed for a higher voltage.

A paper presented at the 288th Meeting of the American Institute of Electrical Engineers, New York, November 14, 1913.

Copyright 1913. By A. I. E. E.

ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES

BY FRANK CONRAD

The principal electrical devices used on the gasoline automobile perform the functions of ignition, lighting and engine starting, their relative importance being in the order given. The service of the first two elements is of a continuous nature; that of the third is intermittent and momentary. The success of the gasoline motor is intimately connected with the success of the ignition system, a condition which has resulted in the development of this device to a high degree of perfection.

The ignition device in its simplest terms consists of a source of electrical supply, an induction coil for producing a high-voltage discharge from an insulated to a grounded electrode in the firing chamber, and a control device or timer for making and breaking the primary circuit of the induction coil. The conditions which have to be met by this ignition system comprises an unfailing source of electrical energy, an igniting spark at all operating speeds and accurate timing of this spark. The dry batteries used in the earlier systems were found to be unreliable. This caused attention to be turned to some form of generator, and due to its greater simplicity and greater range of operating speed, the permanent magnet type, or magneto, was found to be the most suitable. This apparatus possesses several inherent features which are desirable in a spark-producing device. Thus the voltage induced in its windings is approximately proportional to the speed. This tends to maintain a constant spark at all speeds, as the duration of current flow in the primary circuit will be inversely proportional to the speed of the ignition device.

With the advent of electric lighting, a generator of different

characteristics from that of the ignition machine was required. As light is required during periods when the generator is not operating, the use of a storage battery is entailed, and as the generator must operate in parallel with this battery over a wide range of speed, its terminal voltage must be nearly constant over this range. For this reason, and in view of the previous high development of the magneto, it was at first found most convenient to install a separate generator for the lighting system, the ignition thus being operated from a generator having a voltage characteristic approximately proportional to the speed and the lighting system from a generator having a voltage characteristic independent of the speed within its working limits.

As a step towards simplification, it would seem desirable to modify the electric equipment so that a single generator could be used, for furnishing power both to the ignition apparatus and the lighting system. It is of course evident that this generator would require to be of the constant voltage type, as it is necessary that it operate in conjunction with a storage battery. This involves the redesign of the ignition system so that it will operate from a constant potential supply. The earlier form of ignition device, consisting of an induction coil having a vibrating contactor and controlled by a timing device driven synchronously with the engine, met this condition, but it embodied several defects that it was possible to correct in the magneto ignition device. In a simple induction coil device, the contact is made at a predetermined point on the travel of the engine crank shaft, and after the elapsed time required for the current to build up in the primary of the induction coil, it is broken by the magnetically operated vibrator. This vibrator continues to make and break the primary circuit as long as the contact on the engine-driven timer remain closed. The result is a series of sparks in the engine cylinder at each firing period. Due to the fixed time period between the make of the circuit by the timer and the spark in the cylinder, there will be a corresponding lag of this spark as the speed of the engine is increased, thus requiring adjustment of the timer for the particular speed at which the engine is operated in order to obtain efficient results.

To obviate this, the time of break in the primary of the ignition system should be mechanically determined by the rotation of the engine, thereby avoiding the lag inherent in the magnetically operated breaker.

In the magneto device, this condition is met, as no magnetic-

ally operated contactor is used, the primary circuit being opened and closed mechanically by the rotating element. Therefore, there will be no lag of the spark as the speed of the engine is increased. This, however, implies that the duration of current flow in the primary circuit will be correspondingly shorter at the higher speeds. However, as the magneto generates a correspondingly higher voltage; the result will be an increased rate of building up of primary current which will compensate for this shorter time, thus maintaining a constant volume of spark. Unfortunately, in actual practise, this condition will be somewhat overdone, thus at the low operating speeds, the voltage generated will be insufficient to produce normal current flow, owing to the resistance and losses in the device, and, at the very high speeds, the voltage will have increased to such a value that the resistance losses will have a very slight effect, so that the secondary induced current will reach its highest value.

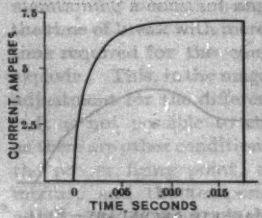


FIG. 1—PRIMARY COIL CURRENT.

In the case of the ignition device operated from a constant-potential circuit and having a fixed angular time of contact, the opposite result will be obtained; that is, at the very low operating speeds, the current in the primary circuit will build up to a value determined only by the resistance of the circuit, while at the very high engine speeds, sufficient time may not have elapsed for the current to build up to a value necessary to obtain a satisfactory spark. It is therefore necessary to introduce some opposing feature which will limit the current at the lower speeds, and still permit of sufficient flow at the higher speeds. A device in which this has been accomplished will have advantages over the magneto, in that it will have no minimum operating speed, and, in addition, at the higher operating speeds, the secondary current will not be of sufficient value to burn away the spark plug electrodes unnecessarily.

The oscillograms show the current wave shape of the primary and secondary circuits of an induction coil used with such a system. Fig. 1 is the primary current, in which contact has been made for a sufficient time to allow the current to build up to its maximum value, which is approximately eight amperes. With

this coil a primary current of about five amperes is required to give a satisfactory discharge in the secondary circuit, and from the oscillograms it can be seen that about 0.003 second is required for current to build up to this value.

In the case of the four-cylinder engine in which the ignition device is driven at engine speed, this would require an arc of contact at 200 revolutions per minute of 3.6 deg., and at 2000 revolutions per minute, 36 deg.

Fig. 2 is an oscillogram of the current in the secondary circuit of this coil. Fig. 3 shows an oscillogram of the secondary circuit of a well-known magneto ignition device. A comparison of the two oscillograms would indicate that the magneto would produce a very much hotter spark than in the case of the constant potential device. Analysis, however, will show that

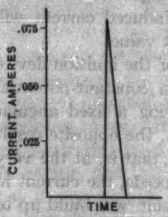


FIG. 2—SECONDARY COIL CURRENT.

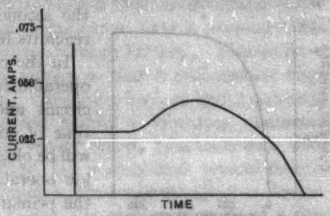


FIG. 3—MAGNETO SECONDARY—FULL ADVANCE

the initial current flow of the two devices is practically the same, the difference being that, in the case of the magneto, this flow is maintained for a considerable period, the maintenance of the current being brought about by the construction of the magneto, in that the primary and secondary windings are wound directly on the revolving armature, the secondary winding therefore cutting the magnetic field by the revolution of the armature, the same as the primary circuit. When due to the interruption of the primary circuit, an induced voltage is set up in the secondary circuit; the current flow across the spark plug electrodes, which is started by this high voltage, will be maintained by the voltage induced by the rotation of the secondary winding in the magnetic field. This continued current flow, however, has no practical advantages, as the explosive gases, which directly surround, and are in range of, the sparking points, are

burned in a period of time probably not exceeding 0.001 second. A continued maintenance of the arc would therefore be of no further value, and would only cause the spark plug electrodes to be needlessly burned away.

An interrupter mechanism for controlling the flow of primary current, and which has been designed in line with the conditions outlined above, is shown in Fig. 4. In this device the angular time of contact is varied with the speed within working limits, so that the primary current will, at all speeds, build up to approximately the same value, thus producing a constant spark in the explosion chamber.

This action is brought about by two centrifugal operating cams which change their position with change in speed so that the contact device is held closed for an approximately constant time. This cam device not only performs the function of maintaining a constant angular time contact, but also advances the time of break with increase of speed to allow for the average time required for the combustible mixture in the cylinder to explode. This, in the magneto device, is accomplished by manual adjustment for the different speeds.

It is not possible to eliminate entirely the manual control, as there are other conditions than that of speed which determine the proper firing point, such as the quality of the explosive mixture and the temperature of the engine cylinders. This adjustment, however, is not required for each change in speed, but rather for the general conditions under which the engine is operating, so that only occasional attention to this control will be required. By the use of this variable contact device, it is possible to operate the coil at its most efficient point, thus obtaining a good spark throughout the working range of speed and with a minimum current consumption.

An advantage of an ignition system of this type is that it is possible to mount it directly on the lighting generator so that it forms part of the same, thus obviating the additional drive which is required in the case of a separate ignition system and, furthermore, it has the advantage over the magneto type, in that it has no minimum operating speed, a spark being produced no matter how slowly the engine is being turned over, thus lending itself particularly to applications in which an electric motor is used to turn over the engine for starting purposes.

As it is desirable that the combined generator and ignition device be installed on the same mounting and drive furnished

for the usual magneto, the generator should be so designed that it will have the proper range of operating speed. For a four-cylinder arrangement this is equivalent to the engine speed, and, on a six-cylinder engine, to one and a half times engine speed. It has been found in practise that it is desirable to have the generator capable of delivering an amount of current equivalent to the average lamp load when the car is being operated at a speed of 15 miles (24 km.) per hour. With the average gear ratio and size of wheels, this would be approximately 500 rev. per min. of the generator, the maximum running speed would be in the neighborhood of 2000 rev. per min. This would give a working range of speed of from 500 to 2000 rev. per min. on the four-cylinder, and 750 to 3000 on the six-cylinder engine.

The illustration, Fig. 5, shows a completed device of this type suitable for a 6-cylinder engine. The induction coil is mounted directly in the high-tension distributor, so that there are no high-tension connections except the leads to the spark plugs on the cylinders. It, therefore, in all respects, will be equivalent to a high-tension magneto of the self-contained type, and has advantages of a constant spark at all speeds, thus giving very good operation at low engine speed, and of furnishing power for lights and charging storage batteries. The regulation of the generator is obtained by means of a demagnetizing series coil in the circuit of the battery, thus maintaining constant charging current. The lighting circuit is so connected that the current supplied directly to the lamps will not pass through the series coil. This tends to maintain a constant charging current independent of the lamp load, and allows of this charging current being adjusted for a minimum value. The curve, Fig. 6, shows the output of this generator at varying speeds, with and without a lamp load of nine amperes.

For starting the gasoline engine, a motor is used which draws power from the storage battery. There are two general schemes possible, namely, the use of the lighting generator as a motor, and the use of a separate motor. The power required for turning over the average engine, at the speeds commonly employed, will range from one-half to one horse power. It is therefore evident that, if the lighting generator should be used as a starting motor, and at its normal operating speed, it would require an extremely heavy machine. In order to reduce this weight, a special driving arrangement might be furnished which would allow the generator to operate at engine speed when

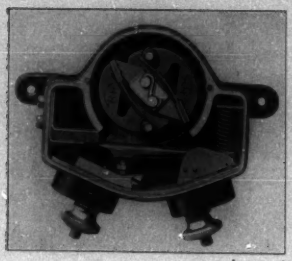


FIG. 4 [CONRAD]

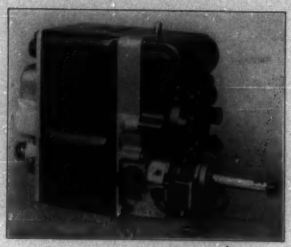


FIG. 5 [CONRAD]

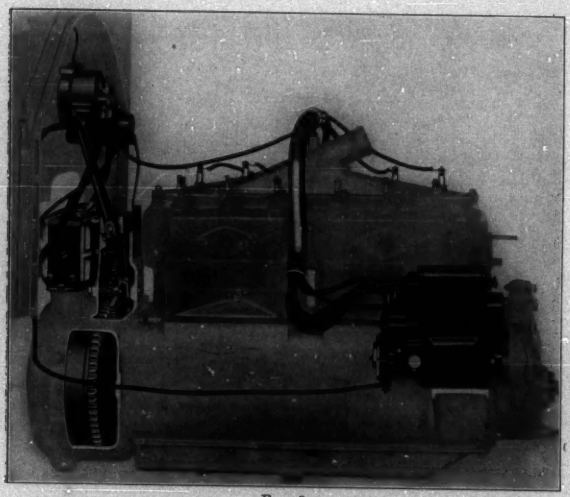


FIG. 9 [CONRAD]

being driven as a generator, and allow a considerable speed reduction from this generator to the engine when being operated as a motor. This implies a low-speed generator and a high-speed motor, which, for efficient design, necessitates double windings and commutators. Due to the general complication of this arrangement, the scheme of using a separate starting motor is to be preferred. This motor can have its proportions best worked out for its operation as a motor, and without the use of any inactive material, which would be necessary in the case of a combination machine. In order to reduce its weight to the lowest possible amount, it should be

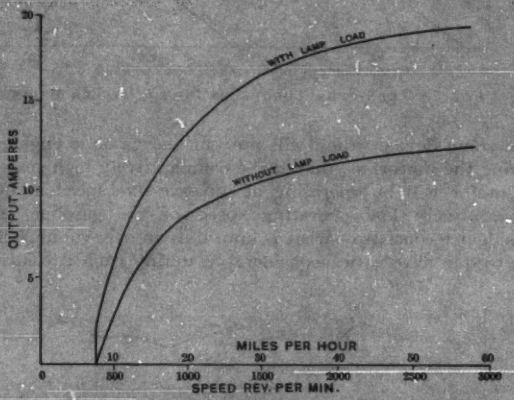


FIG. 6

operated at the highest speed consistent with the use of an efficient gearing between the motor and engine, the normal operating speed, in actual practise, being between the limits of 1000 and 2500 rev. per min., the higher speeds being used where weight is the paramount consideration, and the lower speeds being used where it is necessary that a very quiet drive be obtained.

From the point of view of the design of the motor, there are no particular characteristics required other than those obtained with a series motor. The efficiency should be as high as is consistent with light weight, and the locked torque should be as

great as possible, in order to minimize the possibility of failure to start when the engine is cold and stiff.

In the gearing between the motor and engine, there are certain conditions which must be met, due to the peculiarity of the load which the motor is driving. It is necessary to intro-

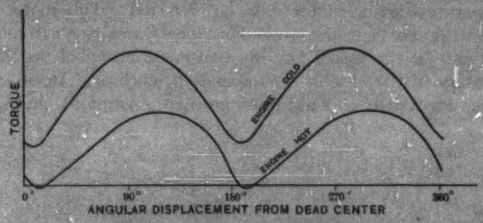


FIG. 7—TURN-OVER TORQUE OF FOUR-CYLINDER ENGINE.

duce some device which will prevent the gasoline engine from driving the motor, as, due to the comparatively high gear ratio, the motor will be operating at an excessive speed at even a comparatively low operating speed of the gasoline engine. This device consists of what is known as an over-running clutch. The torque also varies considerably during each revolution of

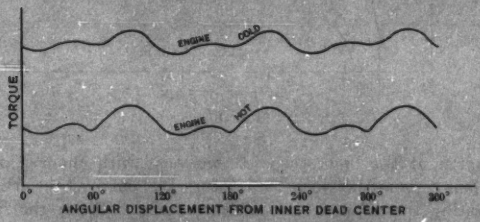


FIG. 8—TURN-OVER TORQUE OF SIX-CYLINDER ENGINE.

the engine, due to the compression and expansion of the gases in the cylinders, this variation, of course, being much greater in a four- than in a six-cylinder engine. The curve, Fig. 7, shows the relative torques required by a four-cylinder engine under two conditions, namely, that of low temperature involving high friction losses due to cold oil in the bearings, and under the

condition of high temperature, which greatly reduces the friction. The curve, Fig. 8, shows the torque required by a six-cylinder engine under the same conditions.

It will be seen that in the case of the hot four-cylinder engine, the torque required to drive it during certain parts of a revolution is negative, the engine thus tending to drive the starting motor. In order to secure a quiet drive, it is essential that, in the disconnecting devices used between motor and engine, there be no appreciable back-lash or lost motion in the over-running clutch device. The effect of this, however, can be minimized by reducing the inertia of the starting motor armature so that it can more closely follow the speed of the gasoline engine over the period of negative torque. The effect also decreases with increase of cranking speed.

As the service of the starting devices is of a momentary nature, it is customary to so proportion the design that the apparatus is worked under conditions of excessive overload, as compared to continuously operated devices. This is particularly true as regards the storage battery, the usual discharge rates being somewhere in the neighborhood of the 20-minute rate. In order to reduce to a minimum the internal drop under this excessive rate, a much thinner plate is used than is the case with batteries intended to be operated only under normal rating. The continuous capacity of the motor should be such that it can completely discharge a fully charged battery under any conditions without injury.

Fig. 9 shows a complete installation on an automobile engine of a set of units as described above. In this application, the starting motor is mounted on the top of the flywheel casing and drives the engine through a gear cut in the periphery of this flywheel, a push button projecting through the dash serving to operate the control switch and shift a sliding pinion into mesh with the flywheel gear.

Where the starting motor is connected to the engine through the medium of a chain drive there is no sliding gear used, but the sprocket wheel on the engine shaft drives through the medium of an over-running clutch. This allows the starting motor to drive the engine, but permits of free running of the engine, independent of the starting motor. The control device consists of a simple switch in the starting motor circuit.

DISCUSSION ON "DYNAMO ELECTRIC LIGHTING FOR MOTOR CARS" (WALLER), "ADVANTAGES OF CLUTCH TYPE GENERATOR AND SEPARATE STARTING AND LIGHTING UNITS FOR MOTOR CARS" (CHURCHWARD), AND "ELECTRICAL EQUIPMENT OF GASOLINE AUTOMOBILES" (CONRAD), NEW YORK, N. Y., NOVEMBER 14, 1913.

H. Ward Leonard: I should like to put before the meeting what I think are a few of the desirable features we should strive to reach in an automatic lighting system for charging a storage battery and operating the lights upon a motor car, and I think the same conditions, so far as the automatic lighting and charging are concerned, may apply equally well to the case of train lighting. These are very broad generalities that I shall specify and while, in each case, they may have been already realized in some one of the various systems, I am not sure that there is upon the market at the moment any one system that contains them all. The points to which I refer are as follows:

1. The automatic regulator shall so control the dynamo output that under all working conditions, including accidental short circuit, the dynamo current shall not exceed its normal full-load rated current.

2. The automatic control shall be such that current will be forced through the battery even if its resistance be abnormally high due to bad sulphating of the plates caused by neglect, the object being to insure the automatic removal of all sulphate, thereby restoring the battery to good working condition.

3. All movable elements of automatic regulating devices shall act independently of dash pots, liquids, frictional driving devices, pivots, oil, grease, graphite, centrifugal devices, and shall be substantially independent of the effects of gravity, and shocks of the road.

4. The automatic regulator shall not have any part subject to wear and therefore requiring adjustment by the operator.

5. The automatic regulator shall be unaffected by any changes of temperature met with in practise, and the dynamo current shall be independent of the changes of temperature to which its windings are subjected in practise.

6. The racing of the engine shall not materially increase the current produced by the dynamo even momentarily, the object being to avoid subjecting the lamps to excessive voltage with consequent blackening and possible instantaneous burnout.

7. As soon as the battery is so fully charged as to be gassing strongly, the current shall be automatically reduced to prevent the driving off of the water of the battery solution.

8. There shall be provided in plain sight of the operator an automatic indicator, which shall continually and positively indicate whether the battery is fully charged or not, and whether

the battery is being charged or discharged, and the value of the current into or from the battery.

9. In case the battery be broken or inoperative for any reason, it shall be possible for the lamps to be operated by the dynamo alone, under ordinary operating conditions.

My experience in this line dates back to the time when, in 1888, I put on the first train lighting system in this country, which operated between Chicago and Milwaukee, and I learned at that time, or thought I did, that the chief problem in a case of this character is to maintain the battery in perfect condition, in a condition ready to perform its duty at all times; and this seems to be equivalent to saying that the battery must be kept absolutely free from sulphate and able to deliver its full capacity. I think that is the case in the lighting and storage system in automobiles where there is such a strong demand made upon the battery relative to the area of the plates. It is necessary to keep that battery in perfect condition all the time if we are going to avoid failures in the future. My opinion of the matter is that this boils down to the statement that the whole problem really hangs upon the design of the controller of the dynamo.

Leonard Kebler: In reading over the paper by Mr. Churchward, I notice a statement which differs from my previous ideas upon this subject.

Mr. Churchward, speaking of the constant-speed dynamo, says: "Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by a bucking series coil, or by regulation of the field current."

This statement is quite contradictory to the theory which I have always held in regard to this matter, and I therefore have had some tests made to check this up.

The theory pertaining to this is that when a motor armature is driven at a constant speed and generates a constant current under any one condition of the battery, with a constant field, then the torque necessary to drive this armature must be constant. The driver of a slipping-clutch-controlled armature varies in speed, but, as stated above, the torque remains constant. The power of the driver is the product of the torque times the speed, so in this case the power will vary directly as the speed.

In practise the clutch begins to slip at a speed of approximately 14 miles (22.5 km.) an hour, and at higher speeds the amperes remain practically constant under any one circuit condition. My theory is that at 42 miles (67.5 km.) per hour the dynamo will require at least three times the power that it does at 14 miles (22.5 km.), although the output remains constant.

The results of my tests indicate that this theory is correct. This additional power necessary at higher speeds is represented by the heat generated by the friction clutch, and by the addi-

tional power necessary to drive the fan which is used to cool this clutch.

This friction of the slipping clutch necessarily entails a certain amount of wear, consequently a periodic readjustment of the clutch is necessary. Otherwise, the ampere charging rate will become gradually lower until the operator's attention is forcibly called to the low rate by the fact that the battery is not sufficiently charged.

Mr. Waller described a system which employs a shunt-wound dynamo having a vibrating arm in the field circuit, this arm being actuated by the armature current, to rapidly insert and cut out a resistance in series with the field, so as to keep automatically a constant armature current. I know from tests made in the past that such a system takes practically the same power to drive at all speeds above say 14 miles per hour, so I assumed that it was more efficient than the one of which Mr. Churchward says, "Its efficiency, even with great slipping of the clutch, is higher than that of a machine controlled by .....regulation of the field current."

The tests made were as follows: A variable-speed electric motor, the speed variation being obtained by inserting resistance in series with the field, was run idle at various speeds in order to find the power necessary to run it idle at these speeds. It was then direct-connected to one of the dynamos equipped with a slipping clutch control, and was run at varying speeds with both the dynamo armature circuit and the field circuit open, in order that we might find the increased power necessary to overcome the friction losses, fan loss, etc., of the dynamo. The same tests were then made with one of the shunt-wound dynamos employing vibratory control in the shunt field circuit, described by Mr. Waller. Then separate runs were made with each of these two dynamos, the dynamo in each case being connected to a three-cell storage battery and the controller arranged in each case to deliver approximately 8 amperes. The results of these tests are shown graphically in Fig. 1.

The tests show that at about 2450 rev. per min. the motor driving the dynamo with the slipping clutch required 2¼ times as much power to drive as it did to drive the shunt-wound machine with the vibrating controller. In each case the amperes generated were about 8.

It should be remembered that this includes the loss in the electric driving motor, and if we deduct the amount of power necessary to drive the driving motor idle at 2450 rev. per min. from the amount of power required when the slipping clutch type machine and the shunt-wound machine respectively were being driven by it, we find that the additional power necessary to drive the slipping clutch machine is practically 3.8 times that necessary to drive the shunt-wound machine with the vibrating regulator.

It is common practise to drive the driving member of the

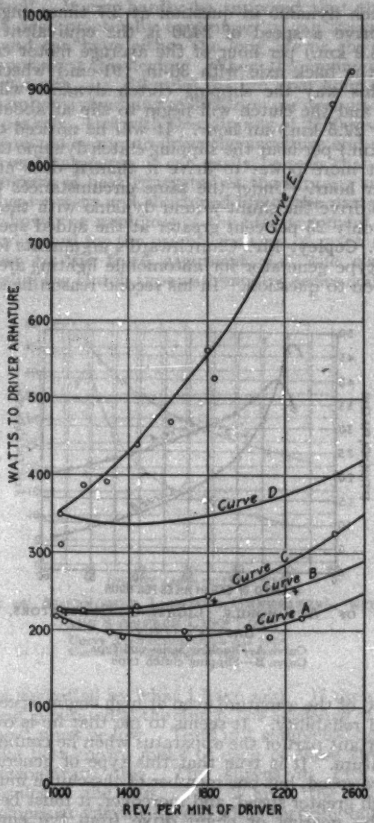


FIG. 1—POWER NECESSARY TO DRIVE DYNAMO WITH SLIPPING CLUTCH CONTROL, AND DYNAMO WITH VIBRATORY FIELD CONTROL, AT VARIOUS SPEEDS.

Curve A—Power taken by driving motor, running idle.
Curve B—Motor driving dynamo with vibratory control, all circuits open.
Curve C—Motor driving dynamo with slipping clutch control, all circuits open
Curve D—Motor driving dynamo with vibratory control, charging three-cell battery at rates varying from 8.2 to 9 amperes.
Curve E—Motor driving dynamo with slipping clutch control, charging three-cell battery at rates varying from 6.5 to 8.5 amperes.

slipping clutch dynamo in question at 2.7 times engine speed. With this drive a speed of 2450 is the equivalent of about 30 miles (48.2 km.) per hour of the average motor car, geared 3¼ to 1 at the back axle with 36-in. (91-cm.) wheels. When geared in this way the slipping clutch dynamo will give its full output, and the clutch will begin to slip at about 13 or 14 miles (21 or 22.5 km.) an hour. It will be noticed that at 30 miles (48.2 km.) per hour the slipping clutch dynamo takes about 330 per cent more power to drive it than it does at 13 miles (21 km.) per hour. Under the same circumstances the power necessary to drive the shunt-wound dynamo with the vibrating regulator is only 25 per cent greater at the added speed.

Almon W. Copley: Mr. Churchward's arguments for the use of a clutch type generator for automobile lighting are in several instances open to question. In his second reason he states that

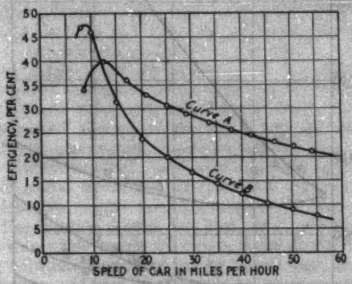


FIG. 2—TEST OF AUTOMOBILE LIGHTING GENERATORS, CHARGING BATTERY ONLY

Curve A—Bucking series coil type
Curve B—Slipping clutch type

the low speed of the armature even at high engine speeds insures long life and reliability. It seems to me that he is overlooking a very important part of the apparatus when he confines himself to the armature. It is true that this type of generator has a low armature speed, but one member of the clutch must revolve at very much greater speed, and moreover, it must be driven at this speed by gearing or chain drive from the engine. Mr. Churchward's curves show that this part must run at about 2½ times engine speed and the problem of driving at this speed is a very serious one. Will not the bearings of this part of the machine wear much more than those of the armature of an engine-speed bucking series coil type generator, or one driven at 1½ times engine speed? The question of the wearing of the chain or gears and the quietness of the drive must also be considered.

But the most objectionable feature of the clutch type machine is

the clutch itself. It can hardly be supposed that this clutch, slipping as it does practically continuously, can stay in proper adjustment and can have either the long life or the reliability of a machine not using this device. When the engine is running at 1500 rev. per min., *i.e.*, 40 miles (64 km.) per hour car speed, one clutch member is revolving at 3750 rev. per min. and the other at 1200 rev. per min., and with this slipping of 2550 rev. per min. there is transmitted energy to drive the armature and charge the battery at 8 or 10 amperes, it can easily be seen that there will be a great amount of heat generated at the slipping surface and consequent heavy wear and shortened life of the parts.

This also shows the weakness of the fifth argument advanced by Mr. Churchward for the use of this type of machine.

The answer to the third argument, *i.e.*, the comparative efficiency of slipping clutch type and bucking series coil type ma-

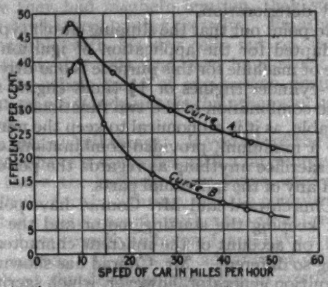


FIG. 3—TEST OF AUTOMOBILE LIGHTING GENERATORS, WITH BATTERY AND 8-AMPERE LAMP LOAD

Curve A—Bucking series coil type
Curve B—Slipping clutch type

chines, is also suggested by what I have said. If there is a large amount of heat generated at the clutch, the efficiency of a machine incorporating it must be low. Tests just completed on the latest designs of the best-known make of each of these two types of machine demonstrate this. The curves in Figs. 2 and 3 show the results of the test. Fig. 2 gives the efficiences of the two machines at varying speeds while carrying only the battery charging current (the lamp load disconnected). Fig. 3 gives the efficiency with an 8-ampere lamp load connected. It seems to me that these show clearly the falsity of Mr. Churchward's theory. The efficiency of the "bucking series coil" type is lower than that of the "slipping clutch" type only at very low car speeds with lights off, and at medium and high car speeds, or at all speeds when the lights are on, the former is very much higher than the latter. The dropping off of the efficiency of the

bucking series coil type at high speed is not such as to indicate extreme core loss under this condition as Mr. Churchward implies.

By reference to the curves the amount of energy absorbed by the clutch can be figured. It is fair to assume that the losses in the armature of the machine are the same at all clutch speeds above 1200 rev. per min., as the armature runs no faster than this. At 1200 rev. per min. the efficiency as shown in Fig. 2 is 40 per cent. The energy supplied the battery is 66 watts. This makes the losses in the armature 99 watts. Now at 50 miles (80.5 km.) per hour (5000 rev. per min.) the energy supplied the battery is the same and the armature loss is the same, totaling 165 watts, while the total energy required to drive the machine is 800 watts. This means that 635 watts are absorbed by the clutch (almost a horse power). The clutch cannot absorb this energy without getting excessively hot and certainly cannot stand this condition without rapid deterioration.

I wish also to point out that the slipping clutch type of machine is not well adapted for the application of ignition parts to it. The best type of machine for this purpose is one driven at engine speed for four-cylinder engines or 1½ times engine speed for six-cylinder. The combination of the two functions in one machine is highly desirable, as it is economical to keep the number of units on the engine a minimum, provided combinations can be made which do not sacrifice anything as regards the performance, life or reliability of any of the individual parts.

Both Mr. Churchward and Mr. Conrad have pointed out the desirability of keeping the starting motor and the generator in separate units, on account of the inherent characteristics of the machines being so different. Mr. Conrad has shown a combined lighting and ignition generator, however, which sacrifices nothing in either the generator or the ignition system. The use of this machine with a starting motor makes necessary only two units; on many of the small engines it is necessary to limit the electrical equipment to this number of units on account of lack of room for more. On the larger engines, also, it is desirable, as it secures the neat, clean appearance of the engine so much sought for by engine and car builders.

I would also take exception to the statement Mr. Waller makes in regard to the merits of the double-wire and single-wire systems of wiring. It should be remembered that almost invariably one side of the battery is grounded—this being done on account of the ignition, which is always of the single-wire system. There is no question as to either the current-carrying capacity or conductivity of the car frame. Therefore, the use of two wires simply introduces an unnecessary complication and a higher resistance return path for the current than the car frame.

With the single-wire system the wire can be better insulated and still take up much less room than the two wires of a double-wire system. The problem of the insulation of the sockets,

lamps, and other fixtures is much simpler with the single-wire system, as more room is available for this purpose. In any electrical circuit of moderate voltage, whether for railway work, lighting or power work, the single-wire system would invariably be used were it not for the problem of obtaining a good ground return on account of such complications as electrolysis, difference of earth potential, etc. None of these complications is met in the automobile frame and there is no reason at all for complicating an inherently simple system by making it two-wire. Single-wire systems are now used quite extensively for car wiring and have demonstrated their practicability and simplicity.

A. D. T. Libby: When the chairman made the statement that the starting and lighting systems were getting down to a point where it was a question of the survival of the fittest, he hit the nail on the head. I believe the whole trend of automobile lighting and starting is fast coming to that point. In the early days, before they had magneto ignition, they started out with four cells of dry battery, giving six volts. Finally some one who had some trouble with his dry cells put on storage batteries equivalent to his dry cells, and they have stuck right along at six volts. The whole trend of engineering, from a power and electric light man's standpoint, is the other way, upward, instead of downward.

There is a mean to all things. If you adopt the 24-volt system, then you must have a controller with a large number of multiple contacts to throw the batteries from series, used in the starting, over to multiple, for the lighting, and the complications involved in this kind of a system are altogether too great for operating in an automobile. I am strongly in favor of, and have always advocated the 12-volt system. It gives the advantages of a higher voltage system without the disadvantages due to complications in the wiring, switches, controllers, etc., and it gives a system which is as simple as the six-volt system, without the many disadvantages thereof. There is no question but that a 12-volt starting motor has more "kick" in it than a six-volt machine. With six volts your brushes are subjected to more or less dust and dirt and you are troubled with these contacts which the low potential will not go through as readily as the 12 volts. I think the final survivor in the starting and lighting work will be the 12-volt system.

The question has been brought up of the single-wire system of lighting cars. There are a number of car makers who are turning out a large number of cars this year with single-contact lamps. I think this kind of a system is wrong. If there is a ground on any one wire of your system, the whole thing is put out of action, while with the 12-volt, two-or three-wire system, or even with the six-volt metallic system, without any ground, if you should happen to get a ground on one wire it will not trouble you at all; in that case you have two chances instead of one. I believe that the single-wire contact systems now being put out will give more or less trouble in the future. They may

not give any trouble while the car is new, and the wiring is in good order, but when the parts begin to get out of order the trouble will start.

The last speaker raised the point that in the one-wire system, the battery being grounded, trouble was experienced in the ignition system when starting on the battery. The company with which I am connected makes an ignition system that operates with or without a grounded battery, it does not make any difference. We can arrange it in any way desired, and that objection would not have any weight so far as this particular system is concerned.

I agree with the argument of Mr. Churchward, and the other gentlemen, in favor of three units. The starting and lighting are entirely different, and should be kept separate on account of the difference in the characteristics of the machines, and it is very evident to one who has gone over this problem that you can build the two individual machines, and get higher efficiency out of each one, than you can by combining the two into one machine. It has been my experience, too, that the simpler you can make a piece of apparatus, especially a thing you put into an automobile, the better off you are; because when it goes into the hands even of the car builders, it is surprising the things they will do to it. The electric motor-starting system has received a black eye, on account of the complications put in, in all the early systems, and it is now being recognized that these complications must go.

There is one point, on the last page of Mr. Churchward's paper, that is a little misleading. That is where he states that the difference between the weight of the batteries in six-volt and 12-volt systems will be 10 per cent. That is, the increase of weight will be approximately 10 per cent, or as much as the weight of the generator unit itself. Now, if he has a generator that weighs 11 lb. (5 kg.) his statement is correct. Otherwise it is not correct, because you can look in the catalogs of prominent automobile battery manufacturers, and you will find that a 100-ampere-hour battery weighs 59 lb. (26.7 kg.), and a 50-ampere-hour weighs 70 lb. (31.7 kg.), a difference of 11 lb. Any generator suitable to charge such a battery does not weigh less than 20 lb. (9.1 kg.).

Mr. Waller states that the battery should be capable of taking the maximum output of the dynamo indefinitely, and Mr. Churchward states that a dynamo which was giving enough current to take care of the lights, would in time overcharge the battery. I think that Mr. Waller's statement is nearer correct than the other in that respect.

Harold Goodwin, Jr.: Taking a previous speaker's objections to the single-wire system as premises, the question may be discussed from the experience of lighting companies. People generally do not test electrical apparatus for grounds until trouble occurs. Therefore, one side of a two-wire system

might be grounded and the automobile would continue to run practically on the one-wire system with all its objections till the second side became grounded. The installation of indicating test lamps to avoid this, would lead to questions and complications worse than the original trouble. Therefore, it would seem that one well-insulated wire with simple wiring will probably be the victor.

C. E. Wilson: I have noted a number of points in the paper by Mr. Churchward, principally in the comparison of the clutch and differential series generators, to which I wish to call attention.

1. The tapering charging current shown in Fig. 1 of the paper is claimed to be due to the fact that the generator is of the clutch type, and the statement is made that the charging current will decrease from ten amperes to about four or five am-

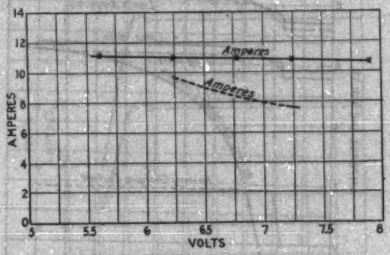


FIG. 4—AMPERES CHARGING CURRENT OF SLIPPING CLUTCH TYPE GENERATOR AT VARIOUS VOLTAGES

Solid line curve, test at constant temperature.
Dotted line curve, replotted from data in Fig. 1 of Churchward paper.

peres when the battery is fully charged, that is, to a voltage of approximately 7.75 volts. A test was made on one of these clutch type generators at variable voltage and the results are shown in Fig. 4 of this discussion. In covering a range from 5.5 to approximately 8 volts the charging current is only reduced about one-half ampere. This test was made with the generator charging a battery, with a booster machine connected in parallel with the battery, thereby making it possible to change the voltage through a wide range. This made a quick test possible and eliminated the effect of heating in the clutch type generator. Comparing the results of this test with Mr. Churchward's curve shown in his Fig. 1, it is evident that the decrease in charging current is due to the heating up of the clutch type generator and is not characteristic of the clutch type generator only. This same effect is noted, possibly to less extent, in the generator of the bucking series coil

type. In fact, a decrease in the charging current from ten to four or five amperes, as stated by Mr. Churchward, caused principally by the increase of resistance in the shunt field and the armature windings, certainly means an excessively hot machine.

2. In showing a typical regulation curve of a generator with bucking series field Mr. Churchward shows (Fig. 2 of the paper) a very poor regulation indeed. On increasing the charging current from 4 to 7.5 amperes the curve shows an increase in voltage from approximately 6.9 to 7.5 volts. In Fig. 4 of the paper, for the same change in charging current a change in the

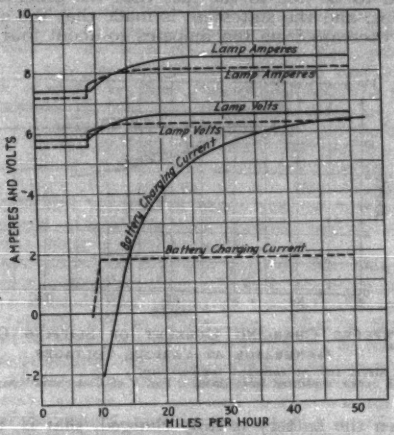


FIG. 5—REGULATION OF AUTOMOBILE LIGHTING GENERATORS
Solid line curves, bucking series field type.
Dotted line curves, slipping clutch type.

voltage from 6 to 6.1 is shown. As this rise in voltage with increase in charging current is due almost entirely to the battery, the increase in voltage should be the same in both cases and not as shown in the two figures. From tests on the two machines which the writer has made personally under the same conditions of battery load, lamp load, etc., the regulations of the two machines are as shown in Fig. 5 of this discussion.

3. In Fig. 3 of Mr. Churchward's paper no data are given as to the speed at which the generator is operating, and the lamp load at the different points. I cannot understand the change in the ampere and voltage curves shown at the end of

seven hours. Also the increase in current shown from the point at 3½ hours to the point at 5 hours is very questionable unless the test was made under some unusual conditions, which I have been unable to duplicate.

4. In Fig. 4 of the paper a current curve is shown increasing from 4 to 7.5 amperes and holding this value for all higher speeds. The title of Fig. 4 is, "Voltage at lamps at different speeds." I do not understand how there can be a voltage at the lamps unless the lamps are turned on, and from tests which I have made on the most recent of these clutch type generators, the current when the lamps are turned on is not 7.5 but more nearly 4 amperes. Probably this same point was overlooked in Fig. 2 of the paper, where the regulation of the differential series generator is shown. It should be remembered that the voltage obtained at the battery without lamp load fluctuates more widely than when the lamps are connected in circuit, for when the lamps are turned on, the battery charging current at a given speed, and thereby the battery voltage, is reduced.

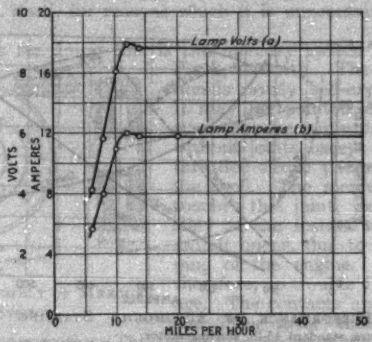


FIG. 6—REGULATION OF SLIPPING CLUTCH TYPE GENERATOR, WITHOUT BATTERY

5. In Fig. 5 of the paper the lamp volts and amperes are shown with the generator disconnected from the storage battery. On making this same test on a clutch type generator of recent design, the regulation was as shown in Fig. 6 herewith. This voltage of approximately 8.75 at all car speeds above 12 miles (19.3 km.) per hour would undoubtedly burn out the lamps in a very short time and make operation on the generator without the battery impracticable. In fact, this point is of very little importance, for in the case of a battery of recent make

with proper terminals, etc., and a good job of car wiring, it is practically impossible for the circuit from the battery to the generator to become disconnected accidentally.

6. In Fig. 6 of Mr. Churchward's paper the performance of what we might suppose to be a typical starting motor is shown. No mention is made of the voltage at which these curves were obtained. The motor operates on a six-volt storage battery whose voltage, especially if the battery contains only 50 per cent or less of charge, drops very rapidly at high currents. As a matter of comparison, I have shown in Fig. 7 herewith a test on a starting motor, of the type described by Mr. Churchward, on the actual voltage which can be obtained on a car. This motor was of the four-pole circular frame type and weighs about 45 lb. (20.4 kg.). The motor whose curve Mr. Churchward shows differs so widely from this standard

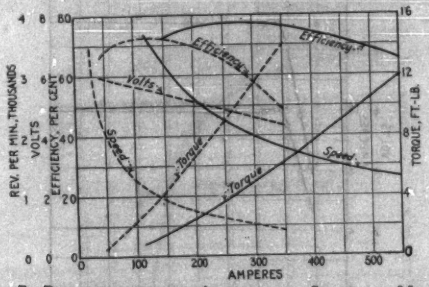


FIG. 7—PERFORMANCE OF AUTOMOBILE STARTING MOTORS

Solid line curves, standard 45-lb. starting motor.
Dotted line curves, performance of motor shown in Fig. 6 of Churchward paper, replotted for comparison.

starting motor that it must be very large and heavy or have some unusual features which should be explained. Another point worth mentioning is the fact that five or six hundred amperes starting current cannot economically be drawn from an 80- or 100-ampere-hour storage battery.

Benjamin F. Bailey: When engineers first began work upon the problem of applying electric lighting to the motor car, most of them proceeded upon the principle that the outfit should be a miniature reproduction of a large storage battery station. The writer of this discussion, on the other hand, has always worked upon the assumption that the simpler the apparatus, provided it would operate, the better. This attitude naturally led to the adoption of the differentially compounded generator. It will unquestionably operate. It involves no moving parts in the regulating apparatus, and the chances of trouble are,

therefore, very remote. There are absolutely no adjustments to be made, as there is nothing to get out of adjustment.

The next problem was to devise a method of connecting and disconnecting the generator from the battery at the proper times. It was desired that this apparatus should be comparable in simplicity with the generator, namely, it must be so simple that it could readily be understood by the average owner or garage man, it must be non-adjustable, and as far as possible, it must be infallible. Particularly, it must never fail to open the circuit when the engine comes to rest.

To secure these advantages the writer was forced to abandon the usual procedure of connecting the generator to the battery when the *voltage* was correct, and instead, make the connection when the *speed* was right. As soon as the connection is made the voltage of a differentially compounded generator automatically adjusts itself, for reasons which it is unnecessary to discuss here.

The means for doing this is the mercury switch shown in Fig. 8, herewith. The construction is nearly self-explanatory. It may be pointed out, however, that the containing shell is without joints, except where the threaded sleeve passes through the shell. The mercury never touches this joint, except possibly at the instant when the switch opens, due to the stopping of the engine. There is, therefore, no trouble from leakage. The contacts are of steel, and even after thousands of breaks show no corrosion. This switch is mounted on the generator shaft inside the housing, and the complete unit, including regulating devices and cut-out, is therefore self-contained.

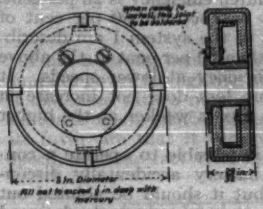


FIG. 8—ASSEMBLY OF MERCURY SWITCH

The writer believes it will be conceded by all that this arrangement leaves little to be desired from the standpoint of simplicity and reliability. It remains to consider what disadvantages, if any, we suffer as compared with the more complicated constant-potential systems. Mr. Churchward mentions five points in favor of his system, in which approximately constant potential is secured by operating the generator at approximately constant speed. A centrifugally operated slipping clutch is inserted between the engine and the generator.

Mr. Churchward's first point is that a constant-potential system charges the battery at a high rate when the battery is low and at a low rate when it is high. The charging rate of a so-called constant-current system is nearly the same irrespective of the charge. Thus there is a small waste of power, and the battery solution loses water faster than would other-

wise be the case. The first consideration is almost trivial, since the cost of the added power to develop the wasted power is too small to consider. Probably it is necessary to add distilled water more frequently to the battery, but the writer has now operated his car for over two months, during which time he has driven over 1000 miles (1610 km.) without adding a drop of water to the battery. The battery had stood without attention and without the addition of water for about two additional months before installation in the car. This is not recommended as a reasonable way to treat a battery. The writer merely wanted to see what would happen to a battery subjected to unreasonable use.

Mr. Churchward makes the statement that the efficiency of a constant-speed generator with slipping clutch is higher than that of a "bucking field" generator. With the former machine, if the constant speed is say 800 rev. per min. it is entirely possible that the driving member of the clutch is revolving at 3200 rev. per min. The torque on the two members of the clutch is the same and the clutch efficiency is 25 per cent. The combination efficiency would be not over 60 per cent of this, or 15 per cent. Actual tests of the system I am describing shows an efficiency of not less than 50 per cent at the above speed, and a somewhat higher efficiency at lower speeds. It must be remembered that the core loss does not increase in proportion to the speed, since the flux is weaker at the higher speeds.

The point is also made that it is possible to operate a constant-potential system with the battery accidentally disconnected. Undoubtedly this is so, but it should be pointed out that the same is true to a certain extent of a properly designed constant-current system. The writer finds that for speeds between 15 and 30 miles (24 and 48.2 km.) per hour, the lighting is satisfactory, and no difficulty would be experienced in getting home with the light generated in this way.

The company with which the writer is associated builds only six-volt systems. We believe that a somewhat more efficient motor may be built for 12 volts, since the commutator loss will be less, but are inclined to think that the greater weight of the 12-volt battery more than makes up for this.

The question whether it is better to have the generator and the cranking motor separate units or to combine the two is still an open one. The writer has designed and built both types. There is little difference in weight. The single-unit system is more convenient from the standpoint of the operator, since, as usually applied, no shifting of gears is necessary, this being accomplished automatically by the mechanism. This is not, however, an invariable rule.

With the two-unit system, it is believed that it is preferable to design the motor powerful enough so that only a single reduction gearing need be used. This is usually accomplished by the

use of a pinion on the motor shaft and a gear bolted to the flywheel or cut in the face of the flywheel itself. This requires a larger and more powerful motor, but the much higher efficiency (due to the lower gear loss) and the saving in the weight and cost of the gearing, will more than offset this. The total gear reduction would be about ten to one.

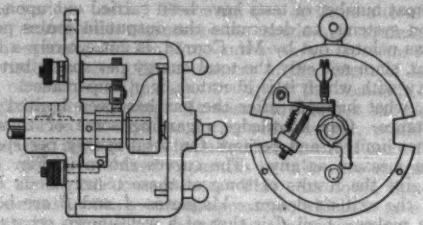


FIG. 9—ASSEMBLY OF TIMER AND DISTRIBUTOR

I am a strong believer in the use of the same system which supplies power for lighting and starting, for ignition also. Since it dispenses with a number of the parts of the magneto it can be made more reliable than the latter. Two strong points in its favor are that it can supply a strong spark even at zero speed, and the fact that the spark advance on a properly de-

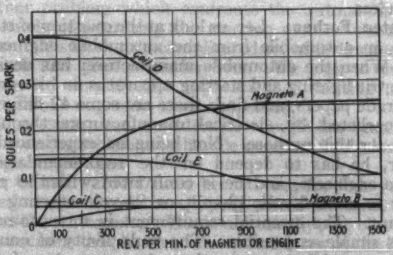


FIG. 10—COMPARATIVE OUTPUTS OF VARIOUS IGNITION SYSTEMS

signed system is absolutely unlimited. This is a point against the magneto which is often not given the attention which it deserves.

In Fig. 9, herewith, is shown the mechanism of the ignition device used in the system I am describing. This arrangement gives a quick break, the speed of the break being absolutely independent of the speed of the engine. Provision is made for

the possibility of a momentary backward rotation of the engine by the use of a double ratchet arrangement applied to the cam.

The arc of contact is constant, and therefore the time of contact is greater for low speed. To avoid too great a difference in the strength of spark at low and at high speeds a "quick" coil is used so that time is afforded for it to become practically saturated even at high speeds.

A great number of tests have been carried out upon different ignition systems, to determine the output in joules per spark. This, as pointed out by Mr. Conrad, is not entirely a fair comparison, since not only the total energy per spark, but also the rapidity with which it is liberated, is of importance. In other words, what happens after the gas has been ignited is of no importance. Our knowledge regarding some of these points is rather limited, and perhaps the total energy per spark is as good a measure as any. The curves shown in Fig. 10, herewith, give the results of some of these tests. Coils *D* and *E* are of the writer's design. Magnetos *A* and *B* are both well-known makes. Coil *C* is that of a well-known constant spark system. All of these outfits gave good results in service, and all except coil *C* have been personally tested by the writer upon actual cars. Coil *D* is the one the writer uses for general purposes. As a matter of fact, coil *E* seems to give as good results, except possibly in starting a very cold motor. Magneto *A* is a very large one weighing over 30 lb. (13.6 kg.), and is intended for low-speed work. The magneto outputs are those obtained at the best point of spark advance. In actual service, at high speed and large angle of advance, the output would be much less.

Kingston Forbes: Let us look at the question of starting and lighting an automobile from the automobile engineer's standpoint. When the automobile manufacturer has decided to install electric lighting and starting apparatus on his cars, he turns to the trade papers, and finds there are some 42 different outfits being marketed by electrical manufacturers throughout the country for this purpose. Not being an experienced electrical engineer, he has to depend on the recommendation of the salesman-engineers, and he is confronted with the problem of whether to use a 6-volt, 12-volt, or 24-volt starting and lighting circuit. The essential requirement in an automobile is to get it as simple as possible. The multiplicity of control in the present automobile is greater than a great many of the operators and laymen care to handle. This makes the simplicity of the electrical apparatus an important consideration. The use of the 12-volt or 24-volt system necessitates complicated wiring and switching, and the automobile manufacturer does not like to confront his customers with this proposition.

Studying this situation carefully, it seems to me that the single-wire system affords the greatest simplicity in respect to the lighting system of the car. In looking over the chassis of a car, if there

is a multiplicity of wires incident to the lighting and starting system it frightens the admirer of the automobile. With the use of the single-wire system, it is possible for the chassis and body to be so wired that by three disconnections the body can be disconnected from the chassis, and the chassis can be so wired that all visible evidence of the wires is practically eliminated.

Another problem connected with electrical apparatus is where to put the various units. There are two or three alternatives offered to automobile engineers—the single-unit system, the double-unit system, and the three-unit system. It seems that it is not advisable to complicate matters to the extent of having one piece of electrical apparatus to supply the demands of ignition, lighting and starting. It seems to me that the electric starting motor in its simplest form, series-wound, would take care of starting, and, going a little further, it would seem that a generator, with a combined apparatus to take care of ignition, should be the logical consequence. This cuts down the electrical equipment to two pieces of apparatus, which, to go a little further, can be coupled up directly to the water pump shaft. By installing the generator like an ignition outfit, connected to the pump shaft, we get a direct-coupled system which is very easy to install when the chassis is being assembled.

As regards the installation of the starting motor, different problems are presented to us, inasmuch as the position of various other parts of the engine is fixed in accordance with the designer's ideas. This makes it necessary for the starting motor to be placed in such a way that it will not interfere with other parts of the chassis.

Still another problem which confronts the automobile engineer is the mode of operating the starting motor—whether by means of a simple switch or a complicated set of levers and overrunning clutch and gear reduction sets. We look to the electrical engineer to simplify the application of starting motors, and the automobile engineers must coöperate.

Up to the present time considerable trouble has been experienced with starting switches to handle comparatively low voltages and high amperages.

Alexander Churchward: I have been trying for four years to get a discussion openly on the slipping clutch machine. All I could get was the statement, "We do not use slipping clutches". But the fact remains that between thirty and forty of the leading automobile manufacturers throughout the United States and Europe are being supplied with the slipping clutch machines and these companies find by actual test that they cannot get similar good results with any other appliance. They would like to be able to dispense with these slipping clutches if they could, but they cannot.

As to criticising the slipping clutches in regard to mechanical adjustment, all I can say is that they do not need as much and as frequent adjustment as the vibrating regulator machines now

in the market. I have seen them tested against the slipping clutch machines which they claim wear so badly, when the latter stood up ten times as long without adjustment as the vibrating regulator machines. That is why so many companies use the slipping clutch machines.

Alfred E. Waller: One of the most deceptive problems the automobile engineer has to face is the old question of the single-wire system with ground return. I believe that most people who recommend the single-wire system are not familiar with its application in automobile work. It is obvious that the metal car frame is capable of carrying current far in excess of the amount required by automobile lamps. The point is that it is not an easy matter to get the current from the lamp terminals to the car frame and from the frame to the battery, due to the difficulty of obtaining good ground connections which will not corrode.

In motor car headlights, as they are made at the present time, the socket that holds the lamp is brazed or otherwise securely fastened into a parabolic reflector of spun metal. The reflector is held in the headlight by an expanding ring which fits in the front cover of the lamp or by some other equivalent means. There is no doubt that the current may be carried satisfactorily on any kind of a continuous metal path, but this method gives a conductor full of joints which may or may not make good contact. You have to start with a socket and get from the shell of the socket to the reflector, and from the reflector to the lamp frame through the expanding ring. Then the circuit runs through the hinge and frame of the lamp to the lamp bracket, then to the car frame. The alternative is a ground wire from the socket to the car frame, and such a wire must not be merely clamped against the frame because it will rust and corrode and consequently make poor contact. You have to drill the car frame and tap it and secure the ground wire by means of a screw set up tight so that you get a continuous metal path which cannot, under any conditions, be affected by corrosion.

It was stated in the discussion that the wiring could be simplified by using a single-wire system. Does it make any difference whether you run two wires in the same sheath or a single wire? The cost of the extra copper for the two-wire system is insignificant. As far as large users of power are concerned, it should be remembered that all of the street cars of New York City are using the metal return. No buildings are wired with a ground return. Very few boats, and none of recent construction, use ground return. The United States Navy has absolutely specified against it after trials which showed it to be unreliable and costly.

Finally, if armored cable is used with the sheath forming the ground return, you have practically the two-wire system with one conductor entirely uninsulated, so that the system is operating at 50 per cent efficiency under the best conditions. I do not understand how any automobile engineer familiar with the difficulty in carrying current through ground connections can be deceived in the matter.

Frank Conrad: The only objection made to the bucking series type of generator was that it does not give the tapering charge described as being desirable for charging the battery. In Mr. Churchward's paper the first advantage given to the clutch type generator is that it charges a battery as it should be charged; that is, with a comparatively large current when the battery is low and empty, tapering off to a small charging rate when the battery is full and at the gassing point.

Fig. 1 in Mr. Churchward's paper gives for the initial charge 9.6, and for the finish about 7.75 amperes, and the battery which will be required for a car installation with a starting motor would stand a continuous rate of 10 amperes, as pointed out by Mr. Waller. It is therefore evident that the initial charging rate obtained by the clutch type generator is no real advantage. Any tapering of the charge is probably due to heating rather than to increase of voltage. Comparative tests have been made of a bucking series generator and a clutch type generator, operated with a resistance load instead of a battery, so that the voltage was constant. The results showed that the actual taper of the bucking series generator is of a greater percentage than the clutch type. That effect is due to the heating of the shunt coil.

In his comparison with the high-voltage batteries, I believe (and the point has been brought up before by another speaker) Mr. Churchward takes a 6-volt battery and divides the plates in two. Of course, if the battery maker were making this battery he could use a different plate to make the capacity even, and then the weight would not be so great.

If the actual increase of weight was 10 per cent, with the average generator with which I am familiar, that would mean a battery weighing 200 lb. (91 kg.), probably 250 lb. (113 kg.).

Alden L. McMurtry (by letter): Mr. Waller's statement that "in practically all instances the system of running two wires to each lamp and fixture has been adopted," may be criticised. Automobile engineers are adopting the one-wire system on account of simplicity, stability, and freedom from electrical troubles.

The automobile wiring problem is entirely different from that pertaining to the street car, steamship or railroad coach. The longest circuit is less than 100 in. (254 cm.), and the troubles encountered are all mechanical rather than electrical. The drop in voltage is less than in the average two-wire system, and the supposedly "poor connections" in the lamp are theoretical.

I have made numerous tests on this subject, and my reasons for advocating the one-wire or grounded system are as follows:

(a) It is stronger mechanically, especially in regard to receptacles; simpler for average operator to locate wire troubles.

(b) It will stand a higher insulation test.

(c) The average electrically-lighted automobile has one side of the battery grounded to the ignition system, and has there-

fore actually a one-wire system, although subject to all the troubles of the two-wire system.

(d) The connections are larger, insuring better contacts at the lamp base.

(e) The amount of current is too small to cause electrical troubles, at connections to the frame of the car.

Inspection of automobiles that have the one-wire system will disprove all arguments used against it.

A point in the discussion of high-voltage systems which is of great importance is the size and form of the tungsten filaments. The six-volt lamp has a small concentrated filament, which makes it easy to focus the lamps. Higher voltage means a longer filament of smaller size, and therefore it will be a difficult matter to focus a searchlight properly. In England, where the 12-volt system is almost universal, the various automobile lamp makers have various forms of reflectors which require a special type of incandescent lamp. This not only lessens the effectiveness of the lamps, but restricts users to lamp renewals supplied only by one manufacturer. The candle power of the tungsten lamp is a secondary consideration to the form of the filament. The distance to which useful light is projected ahead of the automobile is governed by the intensity of the lamp. Lamps of higher candle power cause a greater drop in voltage, and therefore the intensity of the light, and the distance it is projected, is less, while the large area of the filament gives a beam of light of a slightly greater angle.

Some of the arguments against the clutch type of generator are not based on fact. I have personally tested this type of generator over a period of more than 600 hours' continuous running. The wear on the clutch surfaces was not perceptible, owing to the fact that the surface requires very little pressure. I have on my car a clutch type generator, which has been in constant use since December, 1910, and the only attention required was for lubrication, which was needed about once every six months. The rate of current output has decreased approximately seven per cent during this period.

Frederick S. Dellenbaugh, Jr. (by letter): In the early development of any new apparatus correct operation and reliability are of prime importance and the criteria of success. But as the art develops refinements in all directions are introduced and one of the main aims is improvement in efficiency.

This is clearly to be seen in the present case with electric lighting generators for automobiles, and more attention is being given to decreasing the power losses. The gas engines themselves are cut down in every detail to add a little to the efficiency and therefore the choice of a lighting generator, other things being equal, should be governed by the requisite input.

Though of course the most dependable comparisons are based on actual tests, provided they are accurate and made under conditions actually duplicating the ordinary service, it is in-

teresting to investigate the theoretical considerations of the case, as they show what should be expected and, if all factors are included, give approximately correct results.

Except for variations in individual design, the most widely differing types of lighting generators are the constant-speed and the variable-speed types. All the machines built can be included under these heads. In any generator the losses are:

Copper losses due to resistance of windings.

Core losses due to hysteresis and eddy currents in armature core.

Windage losses and friction losses.

Minor losses under load which are practically negligible.

In addition to these we have transmission loss in applying power to the generator.

Taking up first the variable-speed generator, the losses in windings are practically constant as the current in most types is constant.

The windage and friction losses increase with the speed. The windage is very small so that we should expect these losses to be nearly proportional to the speed. In this type of generator the transmission loss can be considered as part of the friction loss.

The variation of the core loss is more complex. Compared to the wide range of speed the voltage can be considered approximately constant.

If ϕ = field flux,
n = speed,
v = volts,
B = flux density,
then volts $= K_1 n \phi$
K being proportionality factor.

Or
$$\phi = \frac{K_1 V}{n}$$

Core loss $= K_2 n \times B^{1.6}$ approximately, as the eddy current loss is a very small percentage of total.

$B = K_3 \phi$ in any one machine, dimensions being constant. Substituting,

$$\text{core loss} = K_4 n \times \phi^{1.6} = \frac{K_5 n \times V^{1.6}}{n^{1.6}} = \frac{K_6 V^{1.6}}{n^{.6}}$$

Thus, if voltage is assumed constant, core loss will decrease slightly as speed increases. Taking the sum of the losses:

Total loss = Core loss + copper loss + windage friction

$$= \frac{K_8}{n^{0.6}} + K_7 + K_9 n$$

If we assume K to make losses equal we have:

$$\text{Total loss} = \left(\frac{35}{n^{0.6}} + 1 + 10^{-3} n\right) K_9$$

If $n = 1000$ rev. per min., total loss $= 3\ K_3$.

If n is increased to 3000 rev. per min., total loss $= 4.56\ K_3$ or an increase of 52 per cent.

Thus, if efficiency were 50 per cent to start with, at 3000 rev. per min. it would now be 39 per cent, or the input would be increased 11 per cent. This is actually a little low, but serves for the purpose of illustration.

In the case of the constant-speed machine, on the other hand, all the losses in the generator itself remain constant and the transmission losses vary. The only successful constant-speed generator that we know of is the one described by Mr. Churchward in his paper, and this uses a clutch which slips above a certain speed. It is evident that for any stable operating condition the torque at the two adjacent faces of the clutch must be the same. The power developed or required is proportional to the torque times the speed, and therefore as the speed of the engine increases, the power supplied to the clutch increases in direct ratio, while the power required to run the generator remains the same.

Evidently, then, if the speed of the engine increases to three times that at which the clutch just begins to slip, the efficiency of transmission must be reduced to 33 per cent, provided it be considered 100 per cent with no slip.

Comparing this with the figures for the variable-speed generator, if we assume slippage to begin at 1000 rev. per min., and efficiency over all at this point 50 per cent as before, and losses $= 3K_3$, then the input $= 6\ K_3$. At 3000 rev. per min., the input to the generator will still be $6\ K_3$, but, as shown above, the power on the high-speed side of the clutch must be three times this, as the torque is the same, and so the input there is $18\ K_3$. Out of 18 units only 3 are being used, as the efficiency over all is now 18.7 per cent.

From this it is evident that the constant-speed machine, whatever its advantages may be in other ways, is inherently extremely inefficient unless some device which will transmit power by transforming torque as well as speed be used, and the variable-speed machine has actually a fairly uniform range of efficiency over its complete range of speed.

John R. King (by letter): Referring to that portion of Mr. Waller's paper wherein he speaks of the necessity of regulating the control of the output of the lighting generator under varying speed conditions, and gives several methods of obtaining regulation, I would like to call attention to a type of generator developed in Germany during the years 1904 and 1905, by Dr. Emmanuel Rosenburg, and used in connection with a storage battery, for lighting railway trains. This apparatus is described in the *Electrical World and Engineer*, Vol. 45, p. 898; Vol. 46, p. 104, and the *Electrical World*, Vol. 48, page 918.

As automobile lighting requirements are similar to those of railway trains, it would seem that unless conditions of design for the smaller units interfere, this type of generator and lighting

system could be applied with success to motor cars. Briefly, the design and operation of this type of generator are as follows: the armature is the same as that in an ordinary direct-current machine, but the field construction is somewhat different, the field poles and frame having a small cross-section and the pole shoes or faces being considerably larger, spanning nearly the entire armature surface, and being notched and cut away at the middle point along the line of the armature conductors. There are double sets of brushes, one set being placed on the ordinary electrical neutral and the other set displaced 90 electrical degrees therefrom. The brushes set on the neutral are short-circuited and current is collected from the displaced set. The simplest type of machine is one that is shunt-wound.

When the machine is started the voltage increases in proportion to the speed until the point of magnetic saturation of the smaller cross-section of the pole pieces and frame is reached. For any further increase in speed, the flux in the field frame is but slightly increased, and the cross-flux created by the coils under the short-circuited brushes tends to counteract this increase, and to hold the current output constant, due to the large stray field in the enlarged pole shoes. The result is that the machine will deliver a constant current with varying voltage conditions over a wide range of speed, or if the outside resistance is constant the machine will deliver approximately constant voltage independent of speed. Other conditions and refinements may be obtained by introducing a series field winding.

Presented at the Detroit-Ann Arbor Section Meeting of the American Institute of Electrical Engineers, Ann Arbor, Mich., December 5, 1913.

Copyright 1914. By A.I.E.E.

FACTORS DETERMINING A REASONABLE CHARGE FOR PUBLIC UTILITY SERVICE

BY M. E. COOLEY

Probably no question of greater importance confronts our people today than the relations of the public and the public service corporations. I refer to relations of a domestic character, rather than foreign, those which affect us as a nation considered as a family in which the interests of all of its members are, or should be, entwined, interwoven, in such manner that whatever is good for one is good for another.

Naturally in treating my subject I shall have in mind ideals which may require years for their realization, but I shall hope to appeal to you with arguments based so firmly on actual facts that I shall not be accused of being academic. I shall endeavor to throw upon my subject the light of nearly fifteen years of experience in the investigation of public utility properties, and I shall hope to leave with you the impression that my views have been expressed with due regard to proper perspective. That is to say, I shall hope to avoid being accused by anyone of even *appearing* to favor one side of the question as against the other. My desire is to speak of what may be seen from the hilltop by any one who will divorce himself from the interests of either side, and try to look upon the problem with unbiased vision.

There are, of course, two sides to this question, as there must be in order that any question can exist. There is the side of the public and the side of the public service corporation. Today they are wide apart. They are wide apart for one principal reason, namely, ignorance. While it may be no disgrace to be ignorant, it is disgraceful to remain ignorant when so little education is required to dispel it. The education required is

not difficult; indeed, it is very simple; but the trouble is that very many of those who most need it are not willing to be educated. Various motives exist, which I will not discuss here, further than to mention that chief among them is a spirit of antagonism, akin to revenge on the part of the public, in localities where the opportunity exists for its manifestation.

It is, I believe, generally considered by the officers of public service corporations that they are, or rather were, themselves responsible for the unfriendly attitude of the public toward them which is now almost general in this country. The public service corporation has in the past proceeded on the theory that the words *public service* had no particular meaning, and that like any other corporation it was at liberty, and indeed had the right, to make as much money as possible out of its business. The public service corporation has in the past ignored the fact that its right to do business is a public grant, a grant which in the very nature of it precluded others from engaging in the same business in the same locality. True, in theory at least, others might be admitted to the field and thus create competition, but practically it has not worked out that way. Ordinarily there is not enough business for two, and even if there were, great inconvenience is likely to result; as for instance in the use of two telephone systems, two waterworks systems, and several street car systems in the same city. It is much to the advantage of the public, both in convenience and expense, to have a single utility of the different kinds serve it when that service can be had on fair terms.

What are fair terms? That is what is partly meant by the words *reasonable charge* in the title of this paper. I say *partly* meant. In the broad sense they may be synonymous. To illustrate: The service rendered by a public service corporation may be very poor without any good excuse for it. In such a case a reasonable charge would be less than when the service was entirely satisfactory. Careless or unintelligent management, or a desire to increase the dividend rate, would lead to this result. Again, the service rendered may be very poor and yet be the best possible and keep the business alive; that is, were the rates higher a better service could be rendered. This may be found in small towns where the extent of the business will not support anything better. Further, the service may be very unsatisfactory and still be the best possible to render regardless of rates; that is, physical conditions may limit

the ability to render satisfactory service. This may be found in large cities, an example being a street railroad system which can not be extended except by building elevated or underground systems.

Fair terms, then, means fair service, or the best possible under the conditions, to the public on the one hand, and a reasonable charge for that service to the corporation on the other hand. They are, or should be, the two members of an equation which are equal to each other. Like an equation, given the service demanded and certain other factors involved, the fair rate, or the reasonable charge, can be readily determined. It is these factors we come now to consider. They embrace, first, the capital investment upon which the interest return is made either in the form of interest or dividends, or both; second, the operating expenses which include maintenance and repairs of all the elements of the physical property, and taxes; third, a depreciation fund out of which can be replaced elements of the physical property which are worn out, or have become obsolete, so that they can no longer be used economically; and fourth, a sinking fund to provide for the loss of the capital due to depreciation, or the difference between the cost of the property when new and when disposed of at the expiration of its franchise life. Let us take them up in order, capital investment first.

It should be understood at the outset that no capital can be made available for a public utility, or for any other business, for that matter, without a sufficient return on the money to tempt its investment in the business. Capital obeys the law of supply and demand like any commodity. Thus, if capital be invited for investment in a service which is desired by the public, then the public must expect to pay the price in the form of interest or dividends which is necessary to secure it.

However much in the past capital may have been tempted into the field without invitation in the hope of large returns, those days are rapidly disappearing; and before very long, if not now, we shall be obliged, not only to extend an invitation, but to offer inducements to bring capital to our door. Those inducements must be not only a fair return on the capital investment but a welcome guaranteed throughout a term of years. Capital may be compared with the guest in our household. While she bides with us she is entitled to the treatment accorded to a guest. She may have worn out her welcome but at the same time have become indispensable to our domestic affairs, so that

we must continue to suffer her presence. We, the public, cannot invite the guest and then while she is with us slap her face; on the other hand, the guest cannot with impunity proceed to rob us once she is in our home.

There is at present a very natural distrust on the part of the public. Capital in the past having very often been self-invited, and having been at first welcome, then tolerated, has finally worn out both welcome and toleration. The logical result, one might think, would be to get along without capital. But of course that would be impossible. Whether the utility be built and operated by the public or by a corporation, capital is necessary. It is true that for a municipally owned utility, capital may be had on more favorable terms with the security which the public can offer; but it does not follow that the service rendered *would* be at correspondingly low rates or reasonable charges. It *could*, perhaps, but the experience of the past favors the belief that such expectation would be utopian rather than practical.

The time is coming, if not already here, when it will make no difference whether capital be invested under the direct security afforded by a municipally owned utility or the more indirect security afforded by a franchise to a corporation. This time will have arrived when the public comes to understand the elements of cost, and all of them, which enter into the construction of a public utility plant. Those elements of cost are the same, or substantially the same, whether the plant be constructed by the public or by the corporation. The public must have a board intrusted with the construction and management of the utility. This board corresponds practically to the corporation's board of directors.

The board, whichever it may be, becomes the agent of the public. It makes the preliminary investigations, employs legal counsel, real estate men to procure the necessary right-of-way, conducts condemnation proceedings, obtains property consents, and attends to all matters connected with the proper launching of the project. It employs engineers to prepare the plans and specifications, invites bids, awards the contracts, and looks after the work during the construction period. It makes arrangements for the necessary funds to finance the project, the necessary working capital, and finally, after the work of construction is completed, puts the plant into operation.

Before its work has been done completely, the business must be thoroughly established; that is, converted from an inanimate

to an animate condition. The earnings from operation must as speedily as possible be brought to a point where they will support all of the expenses. During the period of insufficient earnings, the deficits must be cared for. When the earnings become sufficient to meet all expenses, including interest on the cost of the property, the utility may be said to have become fully a *going concern*.

In all of this work the duties of the board or city officials representing the public, or of the officers representing the corporation, have been the same. The elements of costs have been the same. The principles involved have been the same. The only difference has been one of degree on some of the items, as for instance, less difficulty, possibly, in securing rights-of-way, and more favorable terms in financing. But as already stated, these advantages may in the ultimate results be more *apparent* than *real*. That phase I have no intention of discussing in this paper.

The principal cause of the difference of opinion between the public and the public service corporation, as I have come to see it, lies in the failure of the public to comprehend all of the elements of cost entering into the construction of a public utility plant. Not only that, but a failure also to understand all of the elements of expense which must be incurred in operating the property and maintaining its integrity, once the plant has been built and the business established. The corporation itself is only beginning to understand some of these things. Its officers intrusted with the management of the property have been obliged to make the best of things, striving on the one hand to earn the dividends called for by the stockholders, and on the other, to maintain the property so as to give satisfactory service. Without in any way excusing the corporation from its sins of the past, or of the present where they still exist, the trouble is now understood by the corporation, partly at least; and it must be conceded, I think, that just at present the fault lies more with the public than with the corporation. Let us now take up the elements of cost constituting the capital investment.

It will be easier of understanding if individuals will consider themselves a party to the enterprise. Assume for instance, that you are one of a number of men brought together to consider the building of a public utility property. What is the first step? Naturally you will all want to know whether the project is feasible. This will always involve preliminary investigations,

the sounding of public sentiment to know to what extent the proposed service would be demanded, what concessions would have to be obtained in the matter of property consents and the conditions under which a franchise could be obtained. If these inquiries have resulted favorably, the next step would be to employ engineers to look over the field and make preliminary estimates of cost and determine upon the feasibility of the project. With the information thus far accumulated the bankers must be consulted to determine whether the necessary money can be had. At this point the project may fall through, as there may not be a sufficient promise of financial return to induce capital to come into the enterprise.

All of this preliminary investigation has involved expense which must be borne by someone. It may run from 0.2 to 0.5 per cent of the cost of the proposed property. In case of failure to go further it would fall upon the individuals taking part in the investigation. They have gambled and lost. But should the future promise be great enough to interest capital *mildly*, let us say, then the banker might be induced to gamble a bit, and by being given sufficient odds in the way of discount on bonds and blocks of capital stock depending for their value on future earnings, be induced to come in. The less of gamble there may be, the less the odds demanded by the banks; but at the present time these keepers of the vital life of all business enterprises must, like the well-fed trout, have bait of some form on the hook to interest them at all. Not so, however, with the rank and file who, like the hungry bull-head, bite at anything, even in the dark, if only the light of a candle be exposed to show in the faintest outline the nature of the bait. But public utility properties for the most part are not financed by the rank and file, but by bankers and trust companies. It is, therefore, a real " condition, and not a theory ", which confronts the promoter when he seeks to finance a proposition.

If finally the preliminary work has resulted in the determination to proceed, there comes the organization of the company, the employment of legal counsel to draw up the necessary papers, the procuring of franchises, the obtaining of the necessary property consents, the securing of the right-of-way, by purchase or otherwise, the employment of engineers to make the final surveys and prepare the plans and specifications, the bidding and award of contracts. The actual work of construction then begins.

It is at this point that the public conceives the cost of the

property to begin; and for the reason that the average citizen, skilled as he may be in the work of his own pursuit, has little or no knowledge of the skill required in another's pursuit. Yet this average citizen must be consulted because the project is a public utility. It furnishes him heat, light and power, transports him to his business, and provides him with other fixed necessities of life. This being so, let the condition be met, and first of all let this average citizen be educated to understand the requirements which must be met if he is to be furnished these necessities of our modern civilization. Once he understands there will not be, so far as he is concerned, any further trouble. The average citizen is fair-minded, and asks for only the square deal.

There is, however, another type of citizen who, however much explaining there may be, persists in seeing things his own way. He may be a self-appointed guardian of the people's interest; sincere enough and honest enough, but too often his zeal results in confusion of understanding, if not perniciousness. Another type belongs to the political class. He sees gain in one form or another if he can keep alive the troubles between the public and the public service corporation.

There is no greater service to be rendered the people of our country today than that which could be rendered by the newspapers if they would but go at this matter with the idea of acquainting their readers with the facts on both sides. I mean that they should not treat the quarrels between the public and public service corporations as items of news merely, but detail men on their staffs to make a study of the question involved, bringing to their aid the skill of the accountant, the engineer, the manager, the public officers entrusted with the affairs of these corporations, the business man, and the man who has devoted a lifetime, it may be, to a study of this class of problems. This work should not be done in a haphazard manner, but systematically and with one object in view, namely, to bring about as speedily as possible a clear understanding of all the facts on both sides. Such a work by our newspapers would not only add to the sum total of our happiness, but promote the prosperity and welfare of the communities which they serve. I sometimes wonder why the proprietors of newspapers do not see that their own business is in the nature of a public utility, morally at least.

It is perhaps unnecessary to refer in detail to all of the different items entering into the cost of the physical property of a public utility. Such items as the following are in general capable of being classified in an inventory, and are readily understood:—Land for railroad rights-of-way, electric transmission lines, and pond flowage; land for the many kinds of buildings required, such as office and station buildings, round houses, car barns, power houses for steam and hydraulic plants; and for reservoirs, dams, waterworks, and gas plants. The buildings themselves, together with their furnishings and fixtures. The roadbed, rails, ties and bridges of a railroad; and the locomotive, passenger and freight equipment. The dam structure, water wheels, and generators of a hydroelectric plant. The boilers, engines and generators of a steam plant. The tunnels and pipe lines of a heating plant. The pumping engines, water mains, hydrants and distribution system of a water works. The machinery, gas holders, and distribution system of a gas works. The conduits, manholes and distribution systems of electic lighting and power plants. The switchboard, machinery and apparatus of a telephone exchange; and the wires, pole lines, conduits and instruments of the distribution system. All of these items, and vastly many more, make up the physical structure of public utility plants. They are tangible, that is, they can be seen, counted, measured, weighed, and their costs determined. Materials and labor are the principal items in their creation and installation.

The plans and specifications of a utility plant having been completed, proposals for its construction are invited. The contractor figures the cost of every item as nearly as possible, adding various percentages to cover contingencies, that is, unforeseen difficulties of construction and oversights, some large and some small. He adds the costs of the necessary permits, the insurance required on the men employed and on the buildings during their construction; and finally adds another percentage on the whole for his profits. The propriety of these percentages in figuring the cost of work in advance is so apparent as to cause wonderment that any question should ever have arisen as to the equal propriety of including them in making an appraisal of a property at any time after it was built. Happily this ignorance concerning many of the physical elements has been dispelled, and there no longer is any question of allowing the necessary percentages to cover contingencies, insurance, contractors' profits, engineering and superintendence.

In amount the contingency percentages, varying on the different things from 2 to 20 per cent and upwards, may be assumed to average not less than 10 per cent. One half is usually applied directly to the items themselves, the other half as a percentage on the total cost of all the items. Insurance varies from 0.5 to 1 per cent. The contractor's profit should be estimated at not less than 10 per cent. Engineering and superintendence, like contingencies, varies with the different items from 2 to 10 per cent and over, an average being, say, 5 per cent. One half is applied directly to the items themselves, the other half, as a percentage on the total cost of all the items, including the contingencies and contractor's profits. If the insurance has not been included with the contractor's costs, it should follow after engineering and superintendence, and may then be combined with taxes in a percentage varying from 0.5 to 3.5 per cent. In the application of these percentages, only the *general* engineering percentage should be applied to land, the cost of which embraces its own particular expenses of acquiring, including damages, deeds of transfer and the like.

In case the contract has been awarded to a general contractor he may sublet the different parts to other contractors, each of whom includes in his bid contingencies and other items proper for his particular part of the work and his profits. In such cases the cost of the plant includes, besides the contingencies and profits of the sub-contractor, similar items for the general contractor. A general contractor responsible to the owners for the success of all building operations would probably demand and receive not less than 10 per cent of the cost of the entire work covered by his contract; and instances are known where the general contractor's profit has been large, 20 per cent or more. The measure of his profit is usually determined by the nature of the work, that is, the difficulties and uncertainties involved. The building of the Detroit River Tunnel is an example of where the general contractor made a large profit; but the uncertainties were such that it was not known in advance whether his profit would be large or small, or whether there would not be an actual loss.

Another method in vogue is to place all building operations in the hands of an engineering firm which makes all surveys, prepares the plans and specifications, and superintends the work from start to finish, making a charge therefore of 10 per cent on the actual cost of the work. This virtually amounts to a profit of 10 per cent, as the cost on which the percentage is based

usually includes the salaries and wages of the men employed in the engineering work, and all traveling and office expenses as well. It is known as the "cost plus a percentage" plan. The engineering firm may be likened to the general contractor with this difference: The former takes its percentage on actual costs determined after the work is completed; and the latter, on the estimated costs made before the work is begun. Obviously the uncertainties involved would cause the general contractor to guard himself by making liberal estimates.

We come now to discuss certain other expenses chargeable to capital, but which are not so well understood. Taxes during the construction period is an item usually overlooked by the public. Obviously, any real estate acquired by a corporation for public utility purposes would be taxed the same as similar property owned by an individual. Taxes not infrequently are also imposed on structures built, even before any use is actually made of them. One very common error of the public is to assume that if municipally owned there would be no taxes on a public utility property. True, there would be no taxes levied directly against the property, but there would be the indirect taxes which every taxpayer would have to meet. To illustrate: A public service corporation has to pay certain taxes on its property, and they may be very large. If this property be acquired by the city, it bears no taxes. The same amount of money being required to meet the expenses of government, after as before, it follows that the citizens must make up the amount formerly paid by the corporation. If, however, the earnings remain the same, there will be money to pay the taxes out of earnings. But in that case presumably the rates of charges for service would remain the same, so that one of the alleged benefits of public ownership would disappear. The item of taxes is, in an appraisal, frequently combined with insurance, the amount of the item then varying from 0.5 to 3.5 per cent.

The item of organization, administration, and legal expenses usually follows insurance and taxes and precedes interest during construction. As used by some, the term is rather elastic in being made to include all preliminary expenses, costs of promotion, certificates of necessity, mortgage tax, fees of incorporation, securing of franchises, and other general expenses. It is usually expressed as a percentage varying from 2.5 to 5 per cent, being applied to the sum of all preceding costs, including lands.

There arises in connection with many utility projects certain expenses which have come to be known as costs of promotion and promoter's profits. The terms themselves are rather infrequently used in appraisals, these expenses, if considered at all, being included under costs of administration. Administration is frequently combined with organization and legal expenses. Whatever may be said for and against costs of promotion and promoter's profits in the sense that they represent intangible elements in the nature of "rake-offs", there are, in a totally different sense, certain expenditures during both the construction period and the early operative period which are legitimate and necessary and best described as promotion costs. In the sense that a promoter forwards, advances and encourages, that is, contributes to the growth, enlargement and excellence of a utility project desired by the public, there can be no question that such costs are entitled to consideration in determining a reasonable charge for service.

As to a promoter's profit, its propriety may possibly be decided by considering to what extent one would be willing to contribute to a project, independent of its construction cost, to procure its establishment; or, were a utility now serving the public in some necessary capacity to be taken away, to what extent would you, as one served by it, be willing to contribute rather than lose it. Put it another way: A man says he can make a success of a utility the citizens want, or now have. You doubt its possibility but consent to a trial, and he does it. How much are you willing to compensate him for his energy and brains? This implies a conception free of bias, broad-gaged and just to all interests concerned, which can be had only by being fair and open-minded, and by carefully refraining fron reaching any conclusion in advance. Obviously no percentage could be given for promoter's profits, but appraisals in which the costs of promotion have been ascertainable indicate that a proper charge may be as much as 2 per cent. Its allowance must depend on circumstances, and if included as a separate item, it must of course be excluded from administration costs.

Interest during the period of construction is an important item often overlooked in the past. This means simply that the money which has been expended from time to time during the progress of the work cannot be had without interest. If borrowed, it is secured by interest-bearing notes; and if provided through the sale of bonds, these bonds bear interest. Ordinarily, the interest

charge is based on the assumption that the money expended starts at zero, and mounts uniformly to the total at the end of the construction period. Thus the rate of interest is applied to one-half the total cost, or one-half the rate is applied to the total cost. The construction period varies with different kinds of property, one year, two years, and three years being common lengths of time. It extends to the time when the property is put into operation and begins to earn. A rate of 6 per cent per annum is usually assumed.

The management of a public utility requires a home for its officers and the necessary furniture and fixtures. These may be rented, in which case the rent becomes an operating expense; or the company may own its offices and furniture and the special fixtures needed for its business. The cost then becomes a capital charge. In large properties, street and steam railways particularly, the offices, furniture and fixtures are frequently items of considerable expense. The cost of the equipment of offices, if incurred at the end of the construction period, does not involve interest during the construction period and the item can follow this interest. If, however, it has come earlier, its cost should enter into the sum on which interest during construction is computed.

Certain necessary stores and supplies must be provided ready for use in emergencies before the property can be put into operation. After the plant has been in operation for a time, these gradually adjust themselves as to quantities of the various items. The money represented by stores and supplies can bear no interest unless it be incorporated in the capital, or be carried as a floating debt. In either case the interest on this money becomes a proper charge against earnings. The amount considered is usually an average taken from the books.

Another item which occasions surprise is working capital. By this is meant the money which must always be available to pay bills, labor and the ordinary expenses of operation, and which in the very nature of the fund cannot bear interest except it be incorporated in capital, or be borne as a floating debt with interest paid out of earnings. In either case it becomes a charge against earnings, and therefore takes part as a factor in determining reasonable rates or charges. As between a capital charge and a floating debt it may be pointed out that as a capital charge the rate of interest would presumably be less than as a floating debt. A working capital is as necessary an expense as any other

in the production of a public utility property. Without it the business for which the property was constructed could not be done. How often have we known of the failure of apparently good business enterprises merely for the lack of sufficient working capital. The amount of working capital, like stores and supplies, is usually an average taken from the books.

We have now reached the point at which the property has been completed, having considered items, all of which may enter into the capital investment, and are ready to take up the *second* principal factor, namely, operating expenses. With a working capital to hand, the property has been put into operation. It begins to earn, but a considerable time must elapse ordinarily before the earnings from operation suffice to meet all of the expenditures. By all of the expenditures I mean, interest on the cost of construction, taxes, operating expenses, a fund out of which the expenses of maintaining the integrity of the property can be borne, and another fund to provide for losses of capital at the end of the franchise period. These latter I will discuss separately under the head of "Depreciation" and "Sinking Fund", respectively. During this period of insufficient earnings, money must be borrowed to make up deficits; not only that, but interest must be paid on the borrowed money until the time that the earnings suffice to meet all expenses. This accumulated deficit constitutes what may be termed the cost of procuring a going concern; in other words, the cost of establishing the business. Were the property to change hands at the time the earnings just suffice to pay all expenses, the cost of establishing the business would become the going concern value of the property, and be a part of the total value of the property as a going concern *at that time*. It is a difficult element of cost to determine satisfactorily, in the absence of well-kept accounts, starting with the property itself.

Not infrequently the point is made that the longer it takes to establish the business, that is, the greater the sum of its deficits in earlier years, the greater is its value as a going concern. This apparent inconsistency is explained by the fact that these deficits are real costs, and necessary if the utility is to be had at all. The utility being a necessity, it must be supported by the public the same as any other necessity. The cost of establishing the business therefore becomes a factor in determining reasonable rates or charges. This cost, like that of working capital, if incorporated in the interest-bearing capital, becomes less of a burden against earnings than if carried as a floating debt.

Probably the least understood factor of expense in connection with a public utility property is depreciation. I have called this the *third* factor in determining a reasonable charge for public utility service. By depreciation I mean the money required to to be paid out of earnings in order to meet the expenses of maintaining the integrity of the property. Depreciation is the result of wear and tear and exposure to the elements. It also includes the replacement of machinery which, while not yet worn out, has become obsolete; that is, no longer economical to use; or if still economical, no longer satisfactory to the public. Depreciation includes, further, the wrecking of the machinery due to accident, or to the acts of God.

In the building of a public utility property all of the elements are originally new, but as time goes on these elements suffer wear or decay, some in one degree, some in another. When an element has become worn to a point where it is no longer profitable to keep it in service, it is replaced. Thus in time we have a property which as a whole is made up of old and new elements, the condition of which in the aggregate is something less than the first cost of these elements new. In the very nature of the property it is impossible ever after it is once started to have present in it the full 100 per cent represented by all new elements. It can, however, be maintained in some condition less than 100 per cent, and it is usual and necessary to maintain it at a point which will enable the most satisfactory service to be rendered with the smallest expense consistent with satisfactory service. This point may be anywhere between 80 and 90 per cent, depending on the kind of property.

The expense necessary to keep an element in service during its useful life is a plain operating expense classed under maintenance and repairs, and is not included under depreciation as I am describing it. The depreciation fund is properly a separate fund, maintained as such as distinctly as an interest fund. It is the fund which insures the prolongation of the life of the property indefinitely and always in a condition to render satisfactory service. It is not, however, a fund out of which additions, extensions or betterments may be made, which in their nature constitute additions to capital.

Thus understood, depreciation becomes a factor, and indeed a very important factor in determining reasonable charges for public utility service. Unhappily, the practise of providing this fund is not uniform with the different utilities—not uniform

either in principle or practise. It has long been common for some utilities, railroads for instance, to wear down in lean years and build up in fat years. Thus the condition of the property is not maintained in some uniform condition expressed as a definite percentage of the cost of all new elements, as for example, 80 per cent, but may vary all the way from 75 to 85 per cent.

It is commonly believed by the public that a utility property should not be permitted to earn on more than the so-called present value of its physical elements; that is, their cost new, less depreciation, say 80 per cent of the cost new, or less. As bearing on this I have pointed out that the property, which by means of a proper depreciation fund can be maintained at some definite percentage which enables it to render satisfactory service, has cost 100 per cent. That is, the 80 per cent property can not be had at all without expending the 100 per cent. Thus in order to have an 80 per cent physical condition, we must have a capital charge of 100 per cent. From this it becomes apparent that in determining a resonable charge we must base it not on the percentage which represents condition, but on the cost of the property which cannot be maintained economically above an 80 per cent condition.

If, however, it be insisted that only that percentage of the total cost which is represented by the maintained condition of the property can bear an interest return, the loss of capital and interest thus incurred must be provided for out of earnings in another way, namely, by a sinking fund. This, then, is the *fourth* factor determining a reasonable charge for public utility service. It is to be borne in mind that in this entire discussion I am assuming only actual costs in the capital investment, and only such an interest rate as will induce the investment of the capital in the utility. At the end of the franchise period it is necessary to make good both principal and interest.

The importance of this sinking fund and its magnitude depend on the attitude of the public towards the utility company. The public service corporation works under a franchise, which is simply a grant by the public of the right to do business. With certain kinds of utilities the franchise is perpetual, with others, the life is limited to a definite period, say, 30 years. In some states, Wisconsin for instance, indeterminate franchises are granted; that is, franchises which can be called in, or surrendered, at any time, subject to control by the Railroad Commissionof that state. In the case of a limited franchise under which the utility

company must cease operations and close up its business at the end of a definite period, the company must make not only enough to pay the interest on the cost of the plant and maintain it always in condition to render the service demanded by the public, as well as the operating expenses, including taxes, insurance and repairs, but also an additional amount to cover whatever part of the plant must be sacrificed at the end. This means a sinking fund to retire portions of the cost, if not the entire cost. In other words, the company must earn enough during its life to pay back whatever part of the principal has to be sacrificed, as well as the interest on the principal, in addition to maintaining and operating the plant satisfactorily during its franchise life.

This sinking fund is not always, indeed, I may say, is not generally, kept as a separate account, in this country; but is taken out in the form of distributed earnings from year to year in excess of the amount normally required as interest on the cost. Not infrequently what appears as an abnormally large dividend will on analysis be found to be only sufficient in the end to make good to the investor both the interest on his money and the principal sacrificed when the business is closed out.

It should be clear from this that in general a long term franchise is more favorable to the public, so far as charges for service are concerned, than a short term. To illustrate: assume that the plant must be sold for what it will bring as scrap or second-hand material; the difference between its cost and sale value must be made up out of earnings during the life of the franchise. Thus, if the franchise life be short, say 25 years, the sinking fund annuity must be much larger than if the life be 50 years. No annuity is required, when the life is perpetual. No doubt longer term franchises will be granted in the future, particularly now that the control of them is being lodged by the states in public service commissions.

I am not discussing in this paper conditions which have existed in the past, or may exist, now, in connection with old properties, but am confining myself to fundamental things, those which should guide us in our future relations; those relations which will come to exist when the public service corporation is permitted to earn only enough on its investment to bring capital into the field; that is, the critical condition, as it were.

There remains for me only one more topic, and this I have put off until the last, always shying at it, and going around when possible. I refer to discounts and securities. This I have found:

No bond house will even consider financing a public service corporation without a bond discount. I refer particularly to utilities built and operated under a limited franchise. It will have to be a good property to secure better than 15 per cent discount. It is an excellent property which commands as low as 10 per cent discount. The best discount I have ever come across in my own investigations is 8 per cent. This does not apply to municipalities, however, at least not to the same extent.

The simple conclusion is that if the public utility is a necessity and the money for it is obtained in the usual way, one element of cost is the discount on the bonds, which in effect starts the property off with some water in its securities. It is, or is not, water, as you view it. Anyhow it is necessary in the ordinary way of financing properties. Thus we are obliged, in determining a reasonable charge for public utility service, to consider not merely the actual cost as I have previously given it, but something more, namely, the face of the securities which command an interest return. Opinions differ on whether it is better for this discount to be absorbed as a capital charge or carried as an interest charge. So far as the purpose of this paper is concerned it is not material, as in either case there must be a charge against earnings to take care of the discount.

It will be convenient to bring together the several elements which take part in determining a reasonable charge for public utility service. Not all of them take part at the same time, necessarily, for some may appear in one case and not in another; or several may be combined in a single item. In a general way and in a somewhat natural order, they may be summarized as follows:

First, Capital Investment.

1. Preliminary costs covering investigations as to feasibility of project.

NOTE.– Organization, promotion, administration, and legal expenses, engineering and superintendence during construction, which are distributed over the whole period of construction, are more conveniently placed later in the schedule.

2. The physical property; the several items making up the whole arranged in order, each affected with its proper allowances to cover contingencies, special engineering, and other costs peculiar to the item; land first, followed by clearing and grubbing, then the various structures and equipment; sub-contractors' profits included with separate items.

3. General contingencies applicable to the property as a whole as distinguished from special contingencies applicable to particular items.

4. General contractor's profits; or, the profits to an engineering firm building the property on the "cost plus a percentage" plan.

5. General engineering, and superintendence during construction.

6. Insurance and taxes.

7. Organization, administration, and legal expenses.

8. Cost of promotion, and promoter's profits.

9. Interest during the construction period.

10. Office furniture and fixtures.

11. Stores and supplies.

12. Working capital.

Second, Operating Expenses.

13. Operating expenses *per se*; that is, salaries, wages, fuel and other supplies, repairs and upkeep; all expenditures required in rendering the service of the utility, including insurance and taxes.

14. Interest on the capital investment (the actual cost of the property), *i.e.*, interest on securities which must be paid regularly.

15. Interest on floating debts; this may include the discount on bonds, and the cost of financing, if these have not been incorporated with capital.

16. Cost of establishing the business; the sums of money required to be borrowed, with interest on the same, to make good the differences between the earnings and expenditures up to the time the earnings become sufficient to meet all expenditures. This may be made a capital charge, or carried as a floating debt to be paid out of future earnings.

Third, Depreciation Fund.

17. The regular contribution to the depreciation fund, out of which the integrity of the property is to be maintained.

Fourth, Sinking Fund.

18. The annuity required to retire such portions of the securities as may be necessary at the expiration of the franchise life of the property, in order that the investor may receive back his entire principal when the business is closed out.

It will surprise everyone not familiar with the cost of building utility plants to learn that the so-called over-head charges are in the aggregate a large percentage of the costs of labor and the material things entering into their construction. An examination of the various percentages mentioned in discussing the elements of cost, omitting items 1, 4, 8, 15 and 16, will disclose that if the individual contingencies of construction, special engineering charges, and contractor's profits be assumed to be embraced in item 2, the total percentage may vary from 12 to 25 per cent; and if these inside percentages be added to the outside, or general, percentages, the total percentage may vary from 30 to 60 per cent.

It is to be regretted that engineers, and others who have had experience in building properties, and valuing them afterwards, have not done more towards disseminating knowledge of the actual conditions found in such work. We should then be much further along towards the mutual understanding which must exist before the public and the public service corporation can get together on common ground. But engineers have many times hesitated to use the larger percentages, fearing to be accused of favoring the corporation. They have preferred instead to secure the equivalent of them by using larger units of costs; or have used the smaller percentages, influenced by the feeling, unconsciously perhaps, that all things considered, the results were fair enough. In combining the judicial with their engineering function, they have unwittingly only obscured the issue. All too frequently engineers have felt obliged to exert themselves to the utmost in favor of their client, leaving the interests of the other side to be fought for with equal solicitude by an opposing engineer. Thus they have become advocates. This, in my opinion, is not the best way to handle these momentous problems. It would be far better in these troublesome times to throw open the blinds and let in all the light, our motto being *veritas vincat*.

A paper presented at the 289th meeting of the American Institute of Electrical Engineers, New York, December 12, 1913.

Copyright, 1913. By A. I. E. E.

THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS

BY F. M. FARMER

INTRODUCTION

The object of this paper is to record the results of an investigation which has been made at the Electrical Testing Laboratories to determine the effect of electrode area on the apparent dielectric strength of insulating materials in the form of thin sheets.

It is well known that many conditions affect the results when testing such sheet insulating materials as varnished cambric for dielectric strength. The principal ones are temperature, rate of application of the potential, shape of the electrodes and size of the electrodes. Unfortunately there are, as yet, no standard specifications for testing these materials and each manufacturer, purchaser and testing laboratory uses those methods which seem to be the most satisfactory. In general, varnished cambric and similar materials are tested by placing the sample between, and in contact with, two similar flat circular electrodes to which the potential is applied. The greatest divergence appears to be in the size of the electrodes which vary from needle points to disks 15 in. (38 cm.) in diameter.

The argument advanced in favor of the use of large electrodes is that there is more or less variation in the material, and that the minimum value of the dielectric strength will be found more readily with large electrodes than with small ones. On the other hand, it is contended that the use of very small electrodes introduces an abnormal condition causing concentration of the electrical stress and failure at too low potentials. While much work has been done in investigations of the dielectric

strength of insulating materials, especially air, no data have been published (so far as the writer knows) showing just what effect may be expected with variation in the size of the electrodes, and it is thought, therefore, that the results of some work done in this particular direction will be of interest.

The following tests were made with two, similar, flat, circular electrodes ranging from 1/64 to 6, 10, and 15 in. (0.39 mm. to 15.2, 25.4 and 38 cm.) in diameter and placed directly opposite each other;

1. On insulating cloth and thin sheet hard rubber in air.
2. On insulating cloth in air and in transformer oil.
3. On transformer oil with various spacings.
4. On air with various spacings.

Too many variables enter in tests of this kind to permit a high degree of precision. It is only by taking the average of a relatively large number of readings that even an approximately reliable result can be obtained. However, in these tests, the object was to obtain relative results only, consequently the data should be considered as qualitative rather than quantitative.

Apparatus

Most of the tests were made with a 10-kv-a. transformer connected to a 62.5-cycle, 150-kv-a. generator, but a few of the tests in air were made with two 2-kv-a. transformers. The high-tension voltage was controlled, in all cases, with a variable ratio auto-transformer in the low-tension circuit and measured with a voltmeter connected across the low-tension terminals. Check measurements were made at intervals with an electrostatic voltmeter directly across the high-tension terminals but in no case was any appreciable discrepancy found. Oscillograph records showed that the wave form was practically a sine curve under all conditions prevailing during the tests. The potential was always applied at a very low value (practically zero) and raised gradually and smoothly at a rate of about 1000 to 1200 volts per second. Enough tests (rarely less than ten) were made under each condition to insure an average value of reasonable reliability. The electrodes, which were ¾ in. (9.5 mm.) in diameter and over, were flat brass disks 1/16 to 3/16 in. (1.5 to 4.7 mm.) thick with the corners slightly rounded. The electrodes ¼ in. in diameter and less, consisted of ¼-in. (6.3 mm.) brass rods tapered to the required area at the ends, the corners being slightly rounded.

In all tests on cloth and hard rubber, except those with electrodes over 6 in. (15.2 cm.) in diameter, the electrodes were arranged similar to an ordinary spark gap, being attached to the ends of horizontal rods which were supported by suitable vertical pillars. The specimen was placed between the electrodes which were then brought together with sufficient pressure to insure uniform and complete contact. The pressure was probably never more than a few ounces. Previous tests have

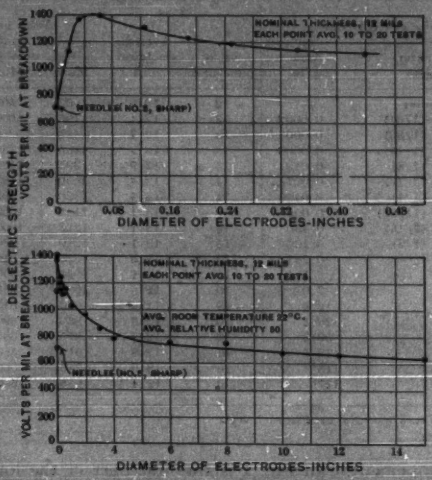


FIG. 1—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WHEN TESTED IN AIR.

shown that wide variations in pressures of this order had no appreciable effect.

TESTS ON INSULATING CLOTH AND HARD RUBBER IN AIR

The results of the tests on varnished cambric (nominally 12 mils thick) are given in Table I and Fig. 1. The lower curve shows that the apparent dielectric strength decreases very rapidly from a maximum value as the size of the electrodes is increased, but that the decrease is relatively slow beyond about

5 in. (12.7 cm.) diameter. The total decrease from the maximum of 1390 volts per mil with 1/16-in. (1.5-mm.) electrodes to 625 volts with 15-in. (38-cm.) electrodes is about 55 per cent of which about 42 per cent took place between the 1/16 in. (1.5 mm.) and 4-in. (10.16-cm.) electrodes.

TABLE I.

VARIATION IN DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WITH VARIATION IN ELECTRODE AREA. ALL TESTS IN AIR.

Size of electrodes		No. of punctures	Average thickness, mils.	Volts per mil at puncture		
Diameter inches	Area sq. in.			Max.	Min.	Avg.
Needles	—	12	12.6	960	505	720
0.0156 (1/64)	0.0002	13	12.4	1195	1000	1135
0.0312 (1/32)	0.0008	18	12.7	1430	1260	1370
0.0625 (1/16)	0.0030	15	12.9	1465	1330	1390
0.125 (1/8)	0.0123	15	12.9	1395	1130	1305
0.1875 (3/16)	0.0276	14	12.4	1330	1135	1235
0.25 (1/4)	0.0490	21	13.4	1320	905	1195
0.344 (11/32)	0.0928	10	13.1	1185	1020	1135
0.438 (7/16)	0.150	14	13.1	1225	1000	1115
0.5 (1/2)	0.196	15	13.1	1240	930	1150
1	0.785	15	12.9	1225	910	1030
2	3.14	10	13.4	1030	890	970
3	7.07	10	12.8	1005	665	870
4	12.6	10	11.9	960	615	790
6	28.3	10	12.3	850	690	755
8	50.3	10	12.8	875	685	755
10	78.5	10	12.8	915	550	680
12	113	10	13.0	745	560	665
15	177	10	12.4	685	530	625

NOTE:—Fresh material used in each test.

The upper curve in Fig. 1 is the first part of the lower curve plotted on a larger scale. This shows that a maximum value is obtained with electrodes about 1/16 in. (1.5 mm.) diameter, lower values being obtained with smaller electrodes as well as with larger electrodes. The results with needles (No. 5, Sharp) are about the same as those obtained with the very large electrodes.

Table II and Fig. 2 show the results of similar tests on sheet hard rubber of 7-, 9-, and 12-in. (17.7-, 22.8- and 30.4-cm.) nominal thickness respectively. These tests were not as extensive as those made on the cloth but the curves have the same general shape although the effect of increasing the size of the electrodes is much less marked.

TABLE II.

VARIATION IN DIELECTRIC STRENGTH OF SHEET HARD RUBBER WITH VARIATION IN ELECTRODE AREA. ALL TESTS IN AIR.

Size of electrodes		No. of punctures	Average thickness, mils	Volts per mil at puncture		
Diameter inches	Area sq. in.			Max.	Min.	Avg.
		(a) Nominal Thickness, 9 mils.				
Needles	—	11	9.0	1970	1275	1705
0.0156 (1/64)	0.0002	13	8.9	2135	1745	1950
0.0312 (1/32)	0.0008	10	8.8	2095	1710	1970
0.0625 (1/16)	0.0030	13	8.8	2100	1600	1865
0.125 (1/8)	0.0123	15	9.0	2105	1075	1790
0.1875 (3/16)	0.0276	14	8.9	2110	1865	1855
0.25 (1/4)	0.0490	15	8.9	2130	1610	1900
0.344 (11/32)	0.0928	24	8.8	2065	1410	1795
0.5 (1/2)	0.196	16	9.0	1945	1510	1800
1	0.785	9	8.8	2045	1570	1860
2	3.14	11	8.8	1820	1600	1720
3	7.07	10	8.8	1715	1330	1530
4	12.6	8	8.8	1570	1245	1410
6	28.3	10	8.8	1300	885	1180
10	78.5	10	8.8	1875	550	1055
		(b) Nominal Thickness, 7 mils.				
0.0625 (1/16)	0.0030	10	7.3	2000	1730	1865
0.5 (1/2)	0.196	10	7.3	1965	1770	1825
1	0.785	10	7.6	1755	1630	1700
2	3.14	10	7.6	1725	1500	1630
4	12.6	10	7.6	1600	1375	1515
6	28.3	10	7.2	1180	875	1060
		(c) Nominal Thickness, 12 mils.				
0.0625 (1/16)	0.0030	10	12.3	1545	1400	1505
0.5 (1/2)	0.196	10	11.7	1620	1185	1460
1	0.785	10	11.7	1600	1225	1425
2	3.14	10	12.3	1365	1230	1300
4	12.6	10	12.3	1380	1200	1235
6	28.3	10	11.7	1165	955	1015

NOTE:—Fresh material used in each test.

The usual explanation for the lower dielectric strength obtained with the large electrodes is that more "weak spots" are included as the area is increased, thus decreasing the average puncture voltage. This explanation would, at first glance, seem to be entirely reasonable for it is well known that in most insulating cloths the insulating material does not penetrate the threads deeply but merely forms a film on the surface of the cloth and, as the threads vary in thickness, the dielectric strength of the points where the threads cross each other will depend upon the thickness of the threads. Where the threads are thick, the

insulating material will be thin, and vice-versa. Similarly, minute variations in the composition of hard rubber might be expected to make "weak spots" when the material is in very thin sheets. It would seem therefore that the greater the electrode area, the greater will be the variation in the weak spots included, until an area is reached such that the weakest spot is always included. Beyond this point the breakdown voltage would therefore remain substantially constant.

On the other hand, as the electrode area is decreased below

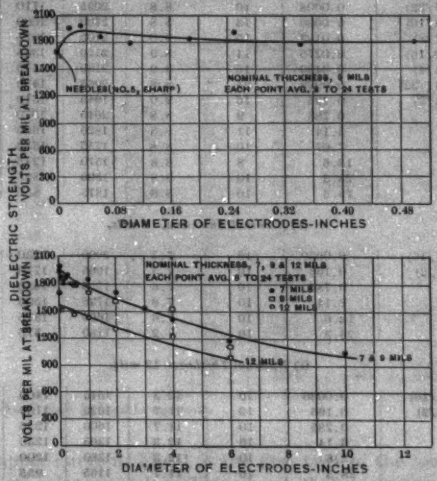


FIG 2.—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF THIN SHEET HARD RUBBER WHEN TESTED IN AIR.

this particular value, one would expect that *occasionally* at least, one of the weakest spots would be included under a given size electrode. An examination of the column of minima in the tables does not show any such result. The figures vary in the same more or less regular manner as do the figures for the average. Furthermore, this explanation does not account for the results obtained with very small electrodes where the most marked effect is found. With such electrodes, it is probable that the air adjacent to the points is broken down long before punc-

ture occurs. This should result in the effective area being increased so that when puncture occurs, this area would be practically the same for all of the very small electrodes. Consequently, according to the weak spot theory, no material variation in the dielectric strength should result with electrodes less than about ¼ in. (6.3 mm.) diameter.

It is apparent from the above that the effect of variation in electrode area is not wholly due to variations in the material. With the smaller electrodes at least, it would appear to be due to the change in the distribution of the electrical stress. As the distribution of the stress in the medium surrounding the electrode terminals would be affected by the nature of that medium, some tests were made in moist air and in oil.

Tests on Varnished Cambric in Moist Air

The first tests were made in a box in which the relative humidity could be kept at practically 100 per cent. Considerable difficulty was experienced in getting results which could be duplicated. The following data are fairly representative:

Diameter of electrodes, inches	Volts per mil at breakdown
1/32	1000
1/2	1010
1	1000
3	975

Relative humidity 98 per cent. Temperature 21 deg. cent.

These figures appeared to indicate that with very moist air, the effect found in the first tests does not occur. This is probably due however to the presence of moisture films on the surfaces of the cloth which make the effective area the same for all of the smaller electrodes.

Shortly after the above tests were made, an opportunity occurred to make some tests under practically outdoor conditions on a very foggy day when the relative humidity averaged 90 to 100 per cent. The results of these tests are as follows:

Diameter of electrodes inches	Volts per mil at breakdown
1/32	1170
3/8	1200
1	1200
3	1060
6	950

Relative humidity 90–100 per cent. Temperature 10 deg. cent. (approx.).

These results do not check with those made in the box, although the variation is much less than in Fig. 1, especially with the smaller electrodes. The lack of agreement with the box test may have been due to the fact that the latter tests were made in a draft in an open doorway while the former were made in a box in which the air was perfectly still and where a film of moisture could probably form more readily.

Tests on Varnished Cambric under Oil

The following tests were made on two kinds of insulating cloth with various sizes of electrodes:

(*a*) In air.

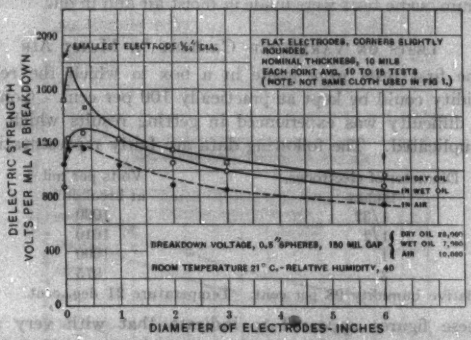


Fig. 3—Varnished Cambric——Effect of Electrode Area on Apparent Dielectric Strength in Air and in Oil.

(*b*) Under moisture-laden oil having a breakdown value between ½-in. (12.7-mm.) spheres, 150 mils apart, of 7000 volts. This test was made on only one kind of cloth.

(*c*) Under untreated oil having a breakdown value of 28,000 volts in one case and 20,000 volts in the other.

The results of these tests are shown in Figs. 3 and 4. It will be noted that, as found in the previous tests, the dielectric strength increases when the electrode diameter is decreased and that it is uniformly greater when the cloth is surrounded with oil than when surrounded with air. It is also to be noted that with very small electrodes the effect of variation in the diameter is apparently somewhat greater with oil than with air.

Further tests were then made with oil and with air as the dielectric to determine whether they would show the same characteristic curve as the solid dielectrics. Since it was a relatively easy matter to change the thickness of the "dielectric" in these tests, curves were taken with various spacings of the electrodes.

Tests with Oil as the Dielectric

The oil used in these tests was a "water-white" oil, taken directly from the barrel and strained through a double layer of fine silk cloth. It had a puncture value between 0.5-in. (32.7-mm.) spheres spaced 150 mils apart of 35,000 volts.

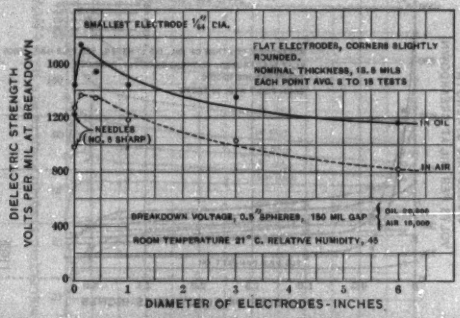


Fig. 4—Black Varnished Cloth—Effect of Electrode Area on Apparent Dielectric Strength in Air and in Oil.

Tests were made with 1/64-, 3/32-, ⅛-, 1-, 3-, and 6-in. (0.3-, 2.3-, 9.5-mm. and 2.5-, 7.6-, 15.2-cm.) electrodes and with spacings of 10, 20, 40, 70,100, 200, 400, and 750 mils.

The results are shown in Fig. 5, from which the following deductions can be made:

(*a*) The dielectric strength increases as the diameter of the electrodes is decreased, *when a thin layer of the dielectric is used*, as strikingly shown by the heavy solid curve which is for 10-mil spacing. This confirms the general result shown in Fig. 1. The effect is, however, much more marked and it is largely confined to the electrodes less than 0.5 in. (12.7 mm.) diameter.

(*b*) The effect of change in electrode diameter decreases as the electrodes are separated, the dielectric strength with the

smaller electrodes becoming smaller and that with the larger electrodes becoming greater. The effect practically disappears at a separation of 400 mils, where the dielectric strength is about 100 to 150 volts per mil irrespective of the size of the electrodes.

(*c*) It is generally known that the dielectric strength of a material is not proportional to the thickness, and that with thin layers especially, the strength increases rapidly as the thickness is decreased. Fig. 5 shows that with 1/64-in. (0.3-mm.) electrodes, the dielectric strength varies from about 90 volts per mil with a spacing or thickness of dielectric of 750 mils to about 900 volts per mil with a spacing of 10 mils. But as the

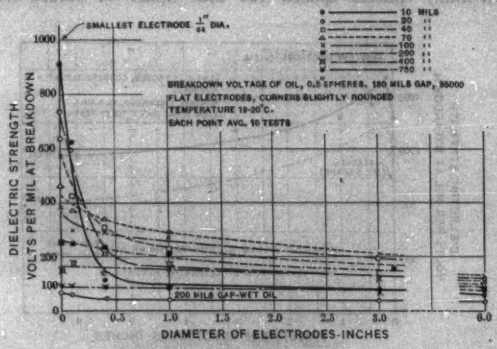


FIG. 5—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF OILS WITH VARIOUS GAPS.

electrode diameters are increased, the dielectric strength becomes more independent of the thickness. At 6 in. (15.2 cm.) diameter, the dielectric strength is practically the same for all thicknesses from 10 mils to 750 mils.

TESTS WITH AIR AS THE DIELECTRIC

These tests were made under ordinary atmospheric conditions and, as only approximate relative data were wanted, no special precautions were taken. The electrodes were simply cleaned by wiping with cloth or filter paper and no attempt was made to have them chemically clean.

The results are indicated in Fig. 6, in which the following will be noted;

(a) As in all previous tests, the electrode area has a marked influence *when the dielectric is thin.*

(b) There appears to be a certain thickness of air (about 100 mils) where the electrode diameter has no effect. With smaller separations, the dielectric strength increases as the electrodes become smaller, and with greater separations the dielectric strength decreases.

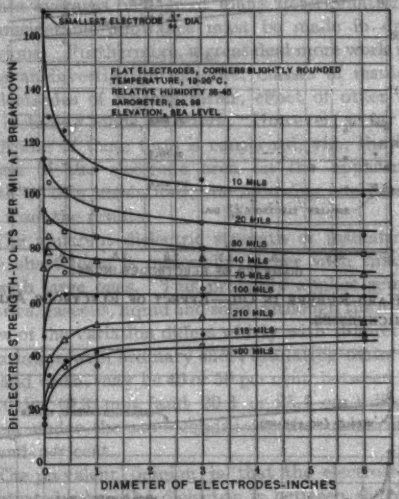


FIG. 6—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF AIR WITH VARIOUS GAPS.

(c) The dielectric strength is higher for thin layers than for thick ones, a characteristic which has been found by many experimenters. Unlike oil, however, the dielectric strength varies inversely with the separation for all sizes of electrodes, but the variation is much greater for the small electrodes.

ADDITIONAL TESTS WITH SOLID DIELECTRIC

The results of the tests in oil and air having indicated that, in those cases, the effect of variation in electrode diameter

occurs only with very thin layers, a few additional tests were made on hard rubber of various thicknesses. These tests were made in oil.

Not enough time or material was available to make these

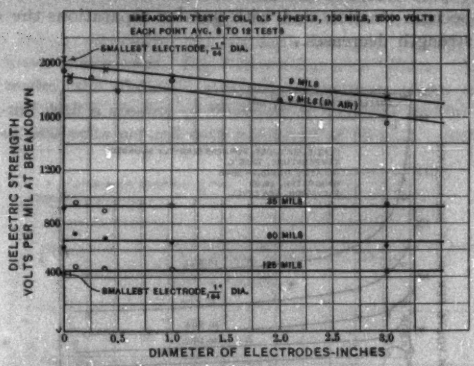


FIG. 7—HARD RUBBER IN OIL—EFFECT OF ELECTRODE AREAS WITH VARIOUS THICKNESSES.

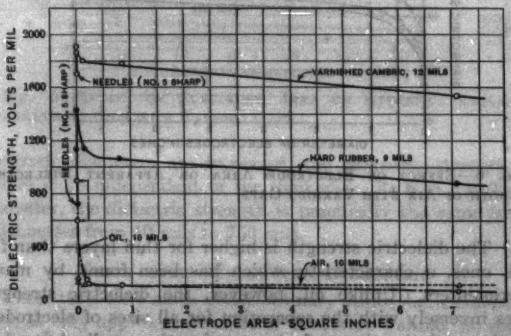


FIG. 8—DIELECTRIC STRENGTH VS. ELECTRODE AREA IN SQUARE INCHES

tests as complete as would be desirable, but the results, as shown in Fig. 7, appear to confirm, in a less marked degree, those found for oil and air. That is, this variation with electrode area is found only with thin dielectrics.

Fig. 8 shows the results for thin sheets of cambric, hard rubber, oil and air, respectively, plotted on an electrode area basis instead of a diameter basis.

Conclusions

In work of this kind, so many variables enter that a high degree of reliability can not be expected. Although the results given are averages of a great many determinations, it is felt that considerable allowance must be made in drawing final conclusions. Furthermore, a great deal more work is necessary, such as an investigation of other classes of insulators, effect with electrodes of various forms, effect of other surrounding media including solids, et cetera. However, so far as the original purpose of these tests is concerned, viz., the effect of the variation of the electrode area on the apparent dielectric strength of thin insulations, the following conclusions may be drawn from the results:

1. The apparent dielectric strength of insulating materials in *thin* sheet form is materially higher with small electrodes than with large ones. This probably applies generally to all dielectrics, gaseous, liquid and solid, although the magnitude and the law of the variation differs widely with different materials. The variation with ordinary sheet insulating materials, such as paper and cloth, may be 40 or 50 per cent between 1/64 in. and 8 or 10 in. (0.3 mm. and 20.3 or 25.4 cm.) diameter, while with oil, under the same conditions, the variation is over one thousand per cent.

2. The prevalent opinion is that the electrostatic stress is concentrated when the dielectric is between sharp points and that failure will occur at a low value. This appears to be the case when the points are very sharp, such as needle points, but as soon as they have an appreciable area, the puncture value is much higher than with large electrodes.

3. The apparent dielectric strength of thin layers of solid dielectrics may vary markedly with the nature of the surrounding medium, being in general, apparently, higher in oil than in air.

4. These tests emphasize a need which has been frequently pointed out in the Proceedings of the Institute, viz., standard specifications for the testing of insulating materials, especially when in the form of thin sheets. It does not seem probable

that the dielectric strength of an insulating material under all working conditions can ever be predicted with exactness, but at least we can have standard methods of rating such materials so that a value for the dielectric strength will have the same significance to the manufacturer, the purchaser and the designing engineer.

DISCUSSION ON "THE DIELECTRIC STRENGTH OF THIN INSULATING MATERIALS" (FARMER), NEW YORK, DECEMBER 12, 1913.

F. W. Peek, Jr.: Three types of insulation are in general use—gaseous, liquid and solid. The mechanism of breakdown differs in many respects in the three types. Any insulation, under given conditions, ruptures at a given point when the dielectric flux density at that point exceeds some definite value. The total dielectric flux depends upon the capacity and the electromotive force; that is, upon the size and spacing of conductors and the voltage between them. The flux density at various points will also be different, depending upon the configuration of electrode. The flux density at any point is proportional to the gradient at that point. The strength of insulation, therefore, may also be expressed in terms of the *gradient measured at the point where rupture occurs.* The voltage required to rupture insulation, divided by its thickness, is not a measure of the insulation strength. It is the average gradient. The maximum gradient where rupture starts is much higher. For instance, take two pairs of spheres, one pair a half-centimeter in diameter, spaced one cm. apart, and the other pair two cm. in diameter, spaced one cm. apart. Apply a voltage of 100 kv. across pair No. 1. The gradient is maximum at the surface and is by calculation $\frac{de}{dx} = 270 \frac{\text{kv.}}{\text{cm.}}$. The average gradient $\frac{e}{x} = \frac{100}{1} \frac{\text{kv.}}{\text{cm.}}$. One pair No. 2, 100 kilovolts gives

$$\frac{de}{dx} = 135 \frac{\text{kv.}}{\text{cm.}}; \frac{e}{x} = 100 \frac{\text{kv.}}{\text{cm.}}$$

Thus for the same voltage and spacing the actual stress is quite different, depending upon the curvature.

If 20-cm. spheres are taken, under the above conditions $\frac{de}{dx} = 103$ and $\frac{e}{x} = 100$. Thus with large radius the average gradients and $\frac{de}{dx}$ are approximately equal. This is the reason that in any investigation (other than commercial testing) made to determine the strength of insulation, some electrode is taken in which the dielectric flux density and gradient at various points can be calculated—that is, spheres, parallel wires, or a wire in a cylinder. These may be arranged so that the break is local, as corona in air on two parallel wires at large spacings. The break starts at the surface because the flux density is a maximum there. The conducting corona extends out approximately to a point where the flux density is below the breakdown density. Only when the surfaces are close

together does a complete spark-over take place before corona forms.

Let us now consider briefly the mechanism of breakdown of three types of insulation.

Air. Air has a greater apparent strength around small conductors than large ones, as for instance, sphere or wires. The explanation apparently is that air has a constant strength of $30 \frac{\text{kv.}}{\text{cm.}}$; rupture, however, does not occur when this gradient is reached at the conductor surface, but only when this gradient is reached at a finite distance from the conductor and when the gradient at the surface is therefore higher. Energy is necessary to rupture insulation. The rupturing energy is stored in this space between the conductor surface where the gradient is high and a finite distance away where the gradient is 30 kv./cm. This distance may be called the energy storage distance, or it may be considered as the distance required to reach ionic saturation by successive collisions between the conductor surface and where the gradient is $30 \frac{\text{kv.}}{\text{cm.}}$, the "accelerating distance."

This distance is $0.301 \sqrt{r}$ cm. for wires, and $0.27 \sqrt{R}$ cm. for spheres. If the conductors are placed closer together than the free energy storage or accelerating distance the apparent strength increases in order that sufficient energy may be stored in the limited space.[1] Although the real strength of air, or the gradient required to bring the ions up to sufficient velocity to produce other ions by collision, is 30 kv. per cm. between parallel planes, with limited energy distance, that is, thin films, gradients as high as $250 \frac{\text{kv.}}{\text{cm.}}$ are required to cause rupture. There is very little loss in air until after rupture, as brush discharge or corona, occurs. For this reason air may be stressed to within a few per cent of breakdown voltage without loss and consequent heating and weakening. Air is uniform and homogeneous and therefore free from "weak spots." The curves given in Fig. 6 of Mr. Farmer's paper are, on account of the characteristics stated above, exactly what would be expected. The ordinate does not represent the dielectric strength, but $\frac{e}{x}$, the average gradient of rupture. The dielectric strength would be represented by $\frac{de}{dx}$. Take for example the curve at

1. This is fully discussed in the following papers by F. W. Peek, Jr.: *The Law of Corona and the Dielectric Strength of Air-I*, TRANS. A.I.E.E. 1911, Vol. XXX, p. 1889; *The Law of Corona-II*, TRANS. A.I.E.E. 1912 Vol. XXXI, p. 1051; *The Law of Corona-III*, TRANS. A.I.E.E., this volume, and "High-Voltage Engineering," in the *Journal* of the Franklin Institute, December, 1913, (No. 1056) page 611.

210-mil spacing. Fig. 1 of this discussion gives curves plotted from data taken from *The Law of Corona-III*, for 0.508-cm. (200-mil) spacing between spheres. Plotted with $\frac{e}{x}$ this gives a curve exactly similar to Mr. Farmer's in Fig. 6. Plotted with $\frac{de}{dx}$, the actual gradient at the surface where breakdown occurs, the curve increases with decreasing diameter of sphere, due to the varying energy distance with varying diameter of sphere. As the radius of the spheres increases, the average gradient curve $\frac{e}{x}$ and the surface gradient curve $\frac{de}{dx}$ come together, because as the radius becomes large compared with the spacing, the flux becomes more nearly uniform.

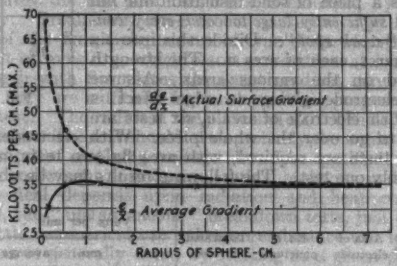


FIG. 1—SPARK-OVER OF SPHERES IN AIR. SPACING = 5.08 CM. (200 MILS.)

Oil. The mechanism of breakdown of pure oil is very similar to that of air and follows the same laws.[2] The constants are, however, different. The energy distance and therefore the apparent strength is much higher. With limited energy distance, strengths as high as a million volts per cm. have been reached with electrodes which gave an apparent strength of $100 \frac{\text{kv.}}{\text{cm.}}$ when the energy distance was not limited.

Solid Insulation. Like air and oil, solid insulations require energy to cause rupture and therefore have a greater apparent strength for small conductors and for small spacings or thin films. If the curves in Fig. 1 in Mr. Farmer's paper were plotted with the true gradient $\frac{de}{dx}$ where rupture starts, and not $\frac{e}{x}$,

2. "High-Voltage Engineering," Franklin Institute *Journal*, loc. cit.

the gradient would increase with decreasing electrode and not show the maximum hump. The curve as plotted does not express the dielectric strength. If this curve were taken at a larger spacing and plotted with $\frac{e}{x}$ the hump would occur at a larger size of electrode. There are conditions where the hump, due to varying energy distance with radius, might actually occur when plotted with the actual gradient. This curve is also affected by the "weak spots", otherwise the curve would be parallel to the axis when the "flat disks" are used. These disks have about equal curvature on the edge, and thus equal effect due to flux concentration. $\frac{e}{x}$ may then be used for comparing strength. This part of the curve practically follows the probability curve.

FIG. 2

For example, suppose Fig. 2 herewith, represents a piece of solid insulation one mil thick and *sufficiently large to cover every condition of "weak spot"*. Divide this into six equal squares, each of area a. The strength is marked on the various areas. Assume that an electrode giving no edge effect is used. With electrode of area a, six tests are required to go over the whole piece. With electrodes of area $2a$ three tests are required, with area $3a$ two tests, and with area $6a$ only one test. The following results may be obtained:

Area of electrode	No. of punctures	Total area covered	Volts per mil		
			max.	min.	average
a	6	6a	20	10	14
2a	3	6a	18	10	13
3a	2	6a	12	10	11
6a	1	6a	10	10	10

The results are somewhat similar to the lower points of the curve in Mr. Farmer's paper. By the method described in the paper, however, the same number of punctures is taken for each size of electrode. Thus for the large electrodes much more insulation is tested than for the small electrodes, and the minimum should therefore be much lower for the large electrodes. In the example I have given, the number of tests is taken so that the total area covered is the same for all electrodes. Thus where edge effect exists it would be more rational to make the circumference covered equal.

With laminated insulation, as in cables, this effect of weak spots should not be so great, as they are not likely to line up in the separate layers.

The curves obtained are therefore probability curves modified by flux distribution (because they are not plotted in terms of maximum flux density), and energy distance.

While loss in air and pure oil is a phenomenon after breakdown occurs, in solid insulation loss occurs as soon as voltage is applied. This heats the insulation and weakens it. It is for this reason generally impossible to hold more than 25 per cent of the "instantaneous" puncture voltage indefinitely. For instance, on a given insulation, if the voltage is brought up rapidly or "instantaneously" 100 kv. may be required to cause rupture; 75 kv. may be applied for one minute before rupture occurs; 50 kv. may be applied for four minutes, and 30 kv. indefinitely. Very high voltages of steep wave front, or of exceedingly short duration, may be applied without apparent effect, but which, upon a number of applications, cause puncture.

The mechanism of breakdown in solid insulation is quite complicated and greatly affected by occluded air and moisture. If a local breakdown occurs, local charring takes place. This concentrates the flux and the break is extended by steps indefinitely. Breakdown often occurs in this way by a concentration of the flux, independent of true dielectric strength, as the result of moisture, which places extra stress at local points.

Although with flat plates the exact gradient cannot be calculated, they are sufficient for most practical purposes in commercial test. The radius of the plate and also of the edge should be specified. The test should also, probably, be made under oil. The method of applying voltage should be specified, as well as material and weight of disk, and method of drying material, etc. A great deal depends upon radiation and heat conduction. After all, the "instantaneous" breakdown tests, just discussed, are of little commerical use unless an endurance test is added—that is, as is generally done, by starting at a given percentage of the instantaneous voltage and increasing by a given percentage at given time intervals until puncture occurs. We will be greatly helped in commercial testing when means of measuring small energy losses are simplified and perfected. In this way the presence of moisture is quickly shown.

Phillips Thomas: Mr. Farmer's paper brings out many points and adds one more link to the chain of evidence, showing the necessity, when giving figures for dielectric strength, of including pretty exact information on the method used in making the tests.

The results at which he has arrived agree in general with those found by the writer and by others for electrode diameters up to ½ in. (12.7 mm.).

As stated in this paper, the law of probability does not seem to apply below ¼ in. (6.35 mm.) diameter of electrodes, and from the nature of the material tested it seems certain that the limiting size of electrode which would always cover the weakest

spot will occur long before 15 in. (38 cm.) is reached. Since the charging current through the dielectric at a given voltage varies inversely as the dielectric thickness and varies directly as the electrode area, any distortion due to this current will react directly on the values found.

In testing various sizes of condensers for breakdown strength, we use an outfit very similar to that described in this paper and have found it necessary to parallel the tested condenser with one of much larger capacity so that the distortion and regulation at a given voltage will not depend upon the capacity of the piece being tested. We have been forced also to measure the breakdown voltage directly at the electrodes, in order to reach comparative results.

The paper states that the voltage reading was checked at intervals by connecting an electrostatic voltmeter directly across the high-tension terminals. Such a check will detect any capacity regulation if made while the test piece is connected, but will not give any information as to distortion. This distortion and regulation will be different for each area and thickness tested and is certain to give misleading results, unless either its presence or its effect is eliminated in some way.

R. P. Jackson: This paper by Mr. Farmer gives some data that are in a way quite surprising and show strongly the importance of having standardized methods of testing insulation materials.

In general, it is my opinion that the lower valued results obtained by Mr. Farmer come nearer the truth in the form in which it is desirable to know it, for the reason that the large area electrodes more nearly duplicate the conditions under which insulation operates and is subject to stress. For that reason the lower valued results obtained with the large area disks apparently give a better guide for the use of the material, and at least as good a guide as to the quality of various grades of similar material.

Different explanations can be offered as to why the results vary so much with the different sizes of electrodes, and the time not being sufficient to duplicate any of the tests, one cannot more than conjecture as to the actual cause of the variation. Varying sizes of electrodes with very thin insulation will, of course, vary the static capacity of the test, and if the supply transformer is small, may cause a rise of voltage at least when the supplied voltage is near its maximum value and the insulation under greatest stress. The condition of capacity and corona or static fringe around the electrodes is liable to cause surges and oscillations which would tend to produce puncture at lower apparent values. Thin air pockets between the electrodes and the insulating material also become sources of corona and therefore heat which might vary with the size of electrodes, especially if the insulating material and the electrodes were not exact plane surfaces and sufficient pressure were not brought to bear to bring

the two surfaces into contact. Another source of variation has been betrayed by similar tests in which thin material failed when the electrodes were of tinfoil of considerable area, and failed at a much lower value than when the electrodes were of small area and of brass pieces of considerable mass. Such tests, however, were of some little duration and the difference in such a case was probably due to the fact that with the tinfoil the heat from insulation losses was not absorbed and the temperature of the insulation rose with corresponding increase of loss until failure occurred. In the case where the massive brass electrodes of small area were used on the same insulation, the mass of the brass and its radiation surface were sufficient to absorb the watt loss in the insulation and kept the temperature moderate and prevented the insulation reaching the unstable condition where the watt loss increased the temperature, and the rising temperature increased the watt loss indefinitely to failure without increase of voltage.

It is the writer's experience that instantaneous puncture voltage tests or tests of very short duration are of rather limited value in furnishing data for judging the use to which the insulation can be put, and only a test lasting long enough to give the approximate ultimate breakdown value with long continued application of the voltage will give the information desired.

C. E. Skinner: As I began insulation work rather early in the art, I think it might not be out of place to review very briefly some of the steps which have been taken in that work. The regular testing of dielectrics and the dielectric tests of apparatus began, with the company with which I am connected, early in the year 1890. At that time we had little or no information to guide us, either as to what dielectric stress meant or anything concerning the effect of the shape of terminals, and 10,000 volts was an almost unheard-of voltage to work with. During the five years that followed, the dielectric testing of materials covered practically every known material and many that probably should have been unknown, and tests of many things that proved not to be dielectrics.

During that early period I think the insulation engineer was one of the most disliked and maligned individuals in the whole engineering profession. The designer calculated to a nicety the copper and the iron, and space used for insulation he considered lost. Furthermore, the more insulation put on, the hotter the machine would get, because the insulating material was also heat insulating material. It was, therefore a constant struggle between the insulation man and those responsible for the rest of the design.

In spite of the more than twenty years of work that has been regularly done since dielectric testing came into vogue as a regular test in practically all large manufacturing establishments, the present state of the art is most chaotic.

I hope that this paper will culminate in a better set of testing specifications. We have heard in the last two days in our

committee meetings a good deal about coöperation. The American Society for Testing Materials has a committee whose duty it is supposed to be to formulate specifications for testing insulating materials. It appears to me that it is more the function of that Society to formulate a detail specification as to methods of testing than it is of this Institute, but that Society cannot do this work without the co-operation of the Institute and it is probably the function of the Institute to formulate something as to the electrical end of this work, I hope that this can be done. I know that a certain amount of work has been done in trying to arrive at a test which will give what we might call the endurance of insulation, which is really the thing that we want to know when we design our apparatus. I agree with Mr. Jackson and others that the instantaneous value is of comparatively little worth in design work. I learned very early to use a very large factor of ignorance in applying the results of my instantaneous values, because I found for example, that when thin sheets of insulating material went into a dynamo, and passed through manufacturing steps, the dynamo, as a whole, would have nothing to compare in dielectric strength with the values per mil which might be obtained on the thin sheets. There are many reasons for this lower value outside of the strength of the material itself; the workmen in the shop may contribute something to lowering the dielectric strength of the materials given them to put on the machine.

I feel that the conclusions arrived at in the paper might possibly be subject to some modification if the tests were made under different circumstances, such as a change in the testing transformer, a change in the method of applying the voltage, a change in the pressure, etc.

I think it would hardly be right in this meeting not to mention the classical work on dielectrics done by Rayner in the National Physical Laboratory. That work followed and completed, for thin materials, a mere start which was made a number of years ago by Mr. Miles Walker and myself, and published in the Institute TRANSACTIONS[3] for the year 1902. Mr. Rayner carried it to a great length, and by measuring the dielectric losses was able to predict when his insulating material was going to break down.

I feel that the future work along this line will have more to do with the study of the power factor, and the study of the dielectric losses, and the study of the endurance of the insulation under continued stress, and I hope that before another year the Institute may be able to adopt the electrical end of a scheme for the endurance test, and possibly for the loss test of insulating materials. I think this paper will do much to bring to us the importance of a standardization of methods, and in such standardization we must necessarily pay attention to every detail in order to arrive at results which would be in any way comparative when made in different laboratories and when made with different materials prepared under different conditions.

3. Vol. XIX, page 1047

H. W. Fisher: When we first commenced to use varnished cloth as an insulation for cables, it was necessary to design an apparatus by means of which we could determine the insulation resistance, the electrostatic capacity, power factor or dielectric loss and dielectric strength of different kinds of cloth. In order to accomplish this, the following apparatus was designed.

Two circular disks were made with a circular groove in each, the inside diameter of this groove being one foot (30.5 cm.). Into these grooves were fitted high-grade rubber gaskets, the ends of each of which almost came together at the top. One disk was mounted rigidly in a vertical position; the other disk was provided with insulators and on an auxiliary frame were four horizontal screws, the ends of which were inserted into insulated posts on diametrically opposite parts of the movable disk. By means of these screws the movable disk could be tightly clamped against the fixed disk so that the rubber gaskets of each would be directly opposite each other. The varnished cloth to be tested was placed between the disks, and pressure applied so as to make a tight joint between the rubber gaskets and the varnished cloth. Attached to the stand of the apparatus was an iron box containing mercury and from the box there were two rubber tubes which connected with a suitable valve at the bottom of each disk. By opening the valves and raising the mercury box, mercury was allowed to flow on each side of the varnished cloth until it reached the small aperture at the top of the rubber disks. Then the valves were closed, the mercury box was lowered to its normal position on the base of the apparatus and the rubber tube attached to the insulated disk was removed, after which the tests mentioned above were made, ending with the breakdown voltage test.

By means of this apparatus, samples of varnished cloth of different manufacture were tested and the power factors were found to vary approximately from four or five per cent to twenty per cent. By making various tests and profiting thereby, the quality of the varnished cloth was very much improved.

It was next necessary to design another type of apparatus for testing cloth in strip form, the way it occurs mostly in the trade. In order to be able to test narrow strips without flashovers around the edges of the strips, the following plan was devised. A strip of brass about ¼ in. (6.35 mm.) wide was placed on a wooden board so that one or two thicknesses of varnished cloth could be put underneath the brass. The brass strip formed the lower electrode of the apparatus. The upper electrode consisted of a copper strip about ⅛ in. (3.2 mm.) wide, mounted on insulated arms so that it could be swung to one side when not in use. The general plan is to put vaseline over the varnished cloth which is placed underneath the lower electrode so that the narrow strip of varnished cloth to be tested

can be placed centrally over the lower electrode and parallel with it and the edges of the cloth pressed firmly into the coating of vaseline, after which the upper electrode is turned over so as to drop in position above the lower electrode. In this way, puncture tests of varnished cloth can be made without any danger of flash-overs around the edges of the strip of cloth tested.

In the testing of cloth with electrodes of different lengths or diameters, care must be taken to proportion the number of tests made to the areas tested. In other words, if a test is made to determine the relation between tests with disks 1 in. (25.4 mm.) in diameter and with disks 20 in. (508 mm.) in diameter, 400 tests should be made with the 1-in. diameter disk, to one test of the 20-in. disk, and the minimum of the 400 tests taken as the tests which ought to correspond to the one test on the 20-in. disk. Bearing this in mind, we made a number of tests which do not show at all the difference indicated by Mr. Farmer's figures. I think that he did not make enough tests of the larger electrodes to get a fair comparison. In order to make a check with a view to determining if the above theory was not correct, we took a roll of cloth and made forty tests consisting of five groups of eight, with electrodes 1 in. (25.4 mm.) long, and then got the average of the minima of these. Next we took the average of ten tests made with electrodes 8 in. (203 mm.) long, and the two sets of measurements agreed within two per cent.

For the same reason just explained, a short length of cable will almost always withstand a higher voltage test than a long length of the same cable.

The old Underwriters' rule was to apply a test of 3000 volts per 1/64 in. (0.397 mm.) of insulation on a one-foot (30.5-cm.) sample. Wire insulated with almost any kind of rubber would withstand that test on a one-foot sample, whereas a coil of wire would break down under the test of 3000 volts per 1/64 in.

M. E. Tressler: Last January when making some very similar tests on yellow varnished cloth I obtained practically the same shaped curves as Mr. Farmer has with various sizes of electrodes from 1 mm. to 100 mm. in diameter with approximately square edges.

A curve showing this variation in disruptive voltage with diameter of electrode for 10 layers of yellow varnished cloth tested under oil at approximately 25 deg. cent. was published last winter[4]. At the same time tests were made on various numbers of layers from 1 to 20 and with electrodes whose edges were rounded to different radii from 0 to 10 mm.

My results do not show such a decided difference between the disruptive voltages with small and large electrodes as do Mr. Farmer's. The maximum disruptive voltage was 1100 volts per mil with a 5-mm. electrode and 810 volts per mil with the 100-mm. electrode.

4. *General Electric Review*. March, 1913—Tressler.

This total decrease is about 26 per cent, of which about 20 per cent took place between the 5-mm. and the 20-mm. electrodes, indicating that tests on thin insulating materials could be made with any convenient size of electrodes from 25 to 100 mm. in diameter and practically the same results would be obtained with a given material.

With greater thicknesses of insulation up to 240 mils, the variation of disruptive voltage with the size of terminal decreases, until at 240 mils there is no difference between the disruptive voltage with 5-mm. and 100-mm. electrodes. However, all of these tests were made by increasing the voltage steadily until breakdown occurred, *i.e.*, the voltage was on from 6 to 12 seconds for Mr. Farmer's tests and from 4 to 8 seconds for mine. This is not a sufficient length of time to allow the

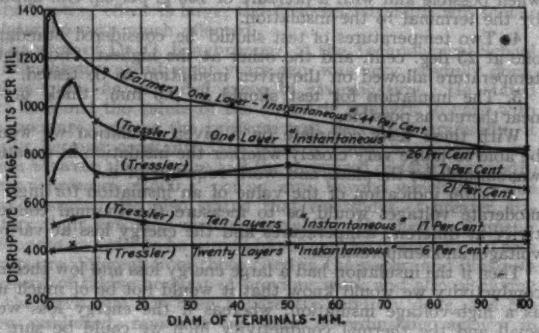


FIG. 3

insulation to be affected by the heat from the energy loss due to the alternating potential.

It would be a much better indication of the disruptive voltage of an insulation under working conditions, if "one-minute" tests were made, *i.e.*, use 50 per cent of the "instantaneous" disruptive voltage as a start for the "one-minute" test and increase by 10 per cent steps each minute thereafter until breakdown occurs.

In general the "one-minute" test will give lower disruptive voltage than the instantaneous test. Sometimes the disruptive voltage increases with increase of temperature and hence we would expect that the "one-minute" test would be equal to or higher than the "instantaneous" test.

If we use the "one-minute" test in finding the effect of terminals of different sizes we will see there is much less dif-

ference between the disruptive voltage with 1-mm. terminals and 100-mm. terminals for any thickness of insulation.

I agree with Mr. Farmer that we are very much in need of standard specifications for the testing of insulating materials, and would recommend, briefly, the following:

1. "One-hour" tests where possible, the "one-minute" puncture voltage being used to indicate the starting voltage for the "hour" test.

2. For testing solid insulations: flat disk electrodes 10 cm. in diameter with practically square edges and insulated on the sides to prevent corona and arcing.

For testing liquid insulations: flat disk electrodes 25 mm. in diameter with practically square edges and spaced with faces parallel and 2.5 mm. apart.

3. All tests of solid insulation should be made under oil when possible and with a pressure of 100 g. per sq. cm. applied by the terminal to the insulation.

4. Two temperatures of test should be considered standard; one at 25 deg. cent. and the other at the highest "hot spot" temperature allowed on the given insulation to be tested.

5. The insulation for test should be 2.5 mm. thick or as near thereto as possible.

With these tests complete on a given insulation we would be able to judge very closely whether the insulation in question was suitable for the place and work required of it.

A better indication of the value of an insulation for high or moderate voltages would be to measure the thermal conductivity at different temperatures and the energy loss at various voltages and temperatures.

Then if the insulation had a large energy loss and low thermal conductivity we would know that it would not be of much use as a high-voltage insulation, whereas if the energy loss were small and the thermal conductivity high we could be sure of a very good insulation, so far as electrical properties are concerned.

Of course we must consider the kind of insulation being used, whether organic or inorganic, how treated and at what maximum temperature it could be run continuously.

In reply to one point brought up by Mr. Thomas, the distortion of the voltage wave across the insulation, I would say that several years ago when testing a piece of insulation of comparatively high permittivity between 25-cm. disk terminals at 50,000 volts, Mr. A. B. Hendricks took an oscillogram of the current wave in the insulation and found it to be practically a sine wave. If there had been any appreciable harmonics in the high-potential voltage wave they would have been magnified by the capacity, in the current wave; hence we may readily assume that, since the current was a sine wave, the voltage also was a sine wave.

E. B. Rosa: I would like to emphasize what has been emphasized already by several of the speakers, and that is the

advantage of having something like standard methods for making insulation tests, and also the advantage of making energy measurements in addition to the breakdown measurements. The measurement of the power factor of the current flowing through such a dielectric reveals wonderful differences, much greater than one would expect. A plate of mica will have a very small power factor, its angle corresponding to the power factor being as small as one minute of arc. That is, the angle by which the current differs from a 90-deg. advance of the e.m.f. is as small as a minute of arc, or smaller. As Mr. Fisher says, in some materials it may be 20 deg., may range anywhere from a minute, or less, to many degrees, so that the heating effect and the energy expended may vary through a range of a thousand to one, and, naturally, if the heating effect is large, the dielectric strength will sooner or later be very much affected.

The work of Dr. C. Kingbrunner, at the Technological School at Manchester, about eight years ago, was very carefully done, and is quite an extended piece of investigation. He stated that he found the values of the dielectric strength to vary with the pressure, and as the pressure was decreased gradually, it finally became constant. He gives a curve showing the relation between the pressure and the measured dielectric strength, using a pressure of 500 g. per sq. cm., beyond which the value was constant. He also stated that electrodes of greater diameters than two cm. vary appreciably. He used a diameter of four cm. in order to be sure to have them large enough. These results are different from those cited in the paper, and illustrate the need of taking account of previous work and also of having all the work that has been apparently carefully done, and has been published, reviewed by some co-ordinating agency in order that the best results may be reduced for all this work.

I was very much interested in what Mr. Skinner said about coöperation in solving such a difficult problem, or, at least, making progress with such an important and difficult problem as this, and as he is so thoroughly convinced of the need of it, it is encouraging, because he is in a fortunate position to bring about such coöperation, as chairman of the committee of the American Society for Testing Materials.

Clayton H. Sharp: The facts in Mr. Farmer's paper, and these other data that have been presented tonight, show more than anything else the elusive character of the problem of testing insulation. It is a case of "now you get it" and "now you don't get it", and just why these curious effects occur is, of course, a matter of very great importance. I do not think that the phenomena which occur are quite so easily explained as one of the speakers tonight would have us believe. Mr. Farmer's results alone show that the matter is more complicated. The question of averages undoubtedly enters, but there is something more than that to it.

Here we have one of the most important elements which enters into the construction of all electrical machinery and apparatus, and it is quite evident that we are unfamiliar with a good many of the fundamental and underlying attributes of this material. It is, therefore, very necessary that further researches of the character of these which Mr. Farmer has made, and of more extensive scope, should be carried on. In the meantime, for the purpose of the practical testing of apparatus, it is of very great importance that some standard specification should be prepared and should be followed.

John B. Taylor: We have here a paper dealing with stresses in insulating mediums, without formulas or mathematical symbols, and yet perhaps of more practical application than some of the papers in the last few years on corona and the distribution of stresses around points, spheres, and other shapes. The curves and results discussed in the paper are quite different from those the theories would seem to lead to. As the paper offers no explanation of these results, it is to be regretted that it is not more complete in a few respects so that the conclusions can be either accepted or doubted for good reason.

There seem to be three factors which may account for the lower breakdown strength per mil as the size of the surface covered is increased. In the first place, if the testing transformer is small, the increase in capacity would tend to raise the voltage on the test specimen without raising it by the same amount on the low-tension voltmeter. Second, as previously brought out, when dealing with a larger sample, by the law of chances we ought to find some weak spots. Third, with the larger sample there is less chance for the radiation of heat. Since all three of these factors work in the same direction, a combination of them may account for the results given.

Mr. Tressler has given some information which corroborates, although not to the same degree, the general character of the results. My own first impression was that the heating was the most likely factor, but this impression does not hold after seeing that the voltage has been brought up at the rate of 1000 or 1200 volts per second, and as the specimens are only 10 or 12 mils thick, the whole test is over in eight or ten seconds. That leads me to ask how it is possible to establish the figures of volts per mil to some four or five parts in a thousand, when the voltage is changing so rapidly.

Also, I would like to ask if the failures in general occur at the edge of the different disks, or whether they are just as likely to occur in the middle.

It would seem desirable to give, in tabulations like these, the average deviation of the results from the mean result. The maximum and mean are given, but the average deviation gives a better idea of the concordance of the observations.

I have a suggestion to make. Many tests of this sort might be made with direct current, which would eliminate some of the

uncertain factors when dealing with alternating current. The heating factor would be eliminated, and also the question of voltage ratio and capacity factor.

A. E. Kennelly: The subject matter of the paper appears upon its face to be very simple. We have here flat electrodes, and except when the electrodes are very small—half a centimeter or less in diameter, we can hardly avoid the conclusion that the stress which ought to be imposed in a uniform dielectric between such flat electrodes is substantially uniform over the entire surface, and we also all believe, I think, that uniform homogeneous material breaks down electrically at the same electrostatic flux density, which means when the maximum local gradient of potential attains one and the same breakdown value.

Starting from this premise, where we would naturally suppose that for the same thickness of material, like varnished cambric the breakdown stress should be the same for different sizes of the different diameter of electrodes, from 0.5 cm. to 10 cm., or more, the values given in the paper show that they are not the same. How are we to reconcile these inconsistencies?

If we assume that there is air pocketed in thin films somewhere, then we have the three dielectrics, air film, varnish film, and the cambric, and these three layers are capable of being associated in various thicknesses which might give rise to variations of electric flux-density and gradient.

It has been pointed out by several of the speakers that one of the conditions involved is the relative chance of including weak spots; but, as has been pointed out by the author of the paper, if that were the case, we should certainly expect what may be called the probable error to be much greater for the little electrodes than for the big electrodes, and if the probable error were greater, the difference between the maximum and minimum voltages of the ten samples would certainly differ very materially, whereas actually, an inspection of the tests indicates that substantially there is the same difference between maximum and minimum voltages in the ten tests on each particular size of electrode. We cannot find an explanation here in the different probabilities of including weak spots.

Since this remarkable variation of dielectric strength with electrode diameter does not seem to be explained satisfactorily, it becomes the more important to standardize the dimensions of test electrodes until the matter has been cleared up.

H. M. Hobart: The subject which is uppermost in my mind at the present time is the need of establishing some relation between the rate of aging of insulating material and the temperature to which it is subjected. From experience with apparatus in service, we have a good idea of this relation up to a little over 100 deg. cent., but we want to consider how far we can go in the direction of higher temperatures with conservatism. As for the range between 110 deg. cent. and 200 deg. cent., the data at our disposal are very meager indeed. The meagerness of our

data relating to aging is rather discouraging. One cannot afford to wait several years for the results of aging tests before employing attractive methods of insulating machines. Nevertheless, the sooner we embark upon elaborate aging tests the sooner we shall have the results commercially available. If a certain material ages imperceptibly at 100 deg. cent., it may age with decided rapidity at 200 deg. cent. If we were to maintain a number of samples at a temperature of 200 deg. cent. the results obtained in a week or a month might be very instructive. We could bake one set of samples at 180 deg., another at 160 deg., another at 140 deg., and another at 120 deg., and take out samples periodically from the ovens. From the results we should be able to establish a curve for that particular insulating material which would give a clue to what we could do with that material in insulating commercial machines. When used in the construction of slot insulation, it might not conform closely to the results which would be obtained by samples tested in the laboratory, but the results would, nevertheless, be indicative.

There is a matter of considerable importance to which I should like to allude. In a paper recently read before the Institution of Electrical Engineers of Great Britain by Mr. S. Eversched, a very interesting footnote appears in which the author states: "The flash test as applied to some costly piece of electrical apparatus must have been inspired originally by something akin to the heroism of the savage." Ever since the time to which Mr. Skinner alludes we have been making tests on electrical machinery not very unlike flash tests. Such tests are still made and are jeopardizing the subsequent life of the machines. The machine may survive the test, so far as we can perceive, but we do not know that we have not caused some serious damage to the machine which will make it of less service during its working life.

W. I. Middleton: In the breakdown tests of cambric cloth insulation, I have used 12-in. (30.48-cm.) electrodes rather than smaller ones, believing the results would be nearer the average breakdown value of the cloth.

My experience with the large and small electrodes has been very similar to that of Mr. Farmer. Between the large and small electrodes, 12-in. (30.48-cm.) and 1-in. (2.54-cm.), I have found an average difference of about 50 per cent increase with the smaller ones. Other investigators have found similar results when investigating along other lines. Mr. Fisher says the short length of cable will stand more voltage than the long length, and my own experiences with the short samples of cables have proved this to be so. Experiments with corona on bare wires have shown that the corona starts at a lower voltage on long lengths than on shorter ones. There is evidently some fundamental law underlying all of these results, although the experiments have been along lines so very different.

In regard to the probability law, we have experimented with

different insulating materials, trying to find one that would give consistent results, and have found none that was as good as air, the oil breakdowns being very irregular. The breakdown of air about the wire, as regards long and short lengths, is so similar to that of other insulations that it would appear to eliminate the law of probability, as we can hardly say that there are weak places in the air.

The chances of wave distortion with any samples of cambric, even as large as 1 sq. ft. (0.0929 sq. m.), seem to be very slight, as the charging current would be very small; this is quite possible where the charging current is considerable, as with long lengths of cables.

The instantaneous breakdown has many advantages in this class of work, if properly applied, as it allows a great many samples to be handled in a short time and eliminates the heating effect, which is one of the most difficult elements to analyze in work of this kind.

I believe we should have a standard size of electrode for this class of work so that the results of tests made by different investigators may be more readily compared, having this large element of doubt as to size of electrode removed.

F. M. Farmer: As to the matter of weak spots—the weak point theory seems to stick with a good many, even though Dr. Kennelly has pretty well covered it. This was pretty thoroughly discussed in the paper. Suffice it to say that it is not at all to be expected that the curves, each point on which is made up of ten tests, would all be smooth and all follow the same general shape. Furthermore, the shape is similar to that obtained for oil where there is no question of weak spots.

The possible effect of distortion with the large electrodes has been mentioned. We went into the matter pretty carefully, and could find absolutely no distortion of the wave with specimens up to 15 in. (38 cm.) in diameter and potentials up to 15,000 or 16,000 volts. A 10-kv-a. transformer was used.

As to the matter of heating, I do not think there can be very much in that as an explanation of these results, because the tests were of such short duration—only a few seconds. From a commercial standpoint the heating should undoubtedly be taken into account. If we want to get at the dielectric strength of the material under operating conditions undoubtedly the temperature has got to be taken into consideration, as also have pressure, and various other things. The point of this paper was simply to call attention to one of the variables and how much it does vary. Each of us is in the habit of making these tests along certain lines, and each has established his own standard electrodes, but it is well to know at least in a general way what the effect of using other electrodes might have been. It was also hoped to show the desirability of standardizing one size, for one size is as good as another because the results are quite empirical,—each designer must apply his own factor of safety.

We have standardized specimens for testing steel, but the designer does not think of using the steel in his structure up to the values given in the test. He allows a factor of safety according to the conditions.

Specifications for insulating cloth should be prepared with a view to enabling us not only to make the tests quickly and cheaply on small samples, but so that everybody will understand what they mean. Then let each individual apply his own factor of safety to suit his own conditions.

Mr. Taylor evidently wanted some more theoretical explanations. There is ample opportunity for those so inclined to make theoretical speculations. I have been unable to formulate a satisfactory explanation and that is why none is offered in the paper. Mr. Peek seems to think the matter very simple, but I do not think so. I do not see how the theory which he advances with respect to cylindrical and spherical electrodes can be applied to flat disks, where the distribution of the flux is very different.

Mr. Taylor apparently has concluded that the potential was measured to five volts and very properly questions such refinement. These figures in the paper are not single measurements, however, but in each case the average of 10 measurements rounded off to the nearest five.

Mr. Taylor asks if punctures appeared near the edges of the electrodes more frequently than elsewhere. The punctures were pretty fairly distributed over the entire surface, which I think is accounted for by the rounded corners.

J. W. Milnor (communicated after adjournment): There has been considerable speculation concerning the causes of the phenomena observed by Mr. Farmer, and in view of this an analysis based on the theory of probability should be of interest.

Let it at first be assumed that the electric field between the electrodes is uniform, the increased flux density near the edges being ignored. The total area of the insulating material under test may be considered to be made up of a large number of elemental areas dA having an average dielectric strength E_a, this value being very high. Their dielectric strength should vary according to the well-known law of error. That is, the probability curve of dielectric strength of an element of area is

$$P = \frac{h}{\sqrt{\pi}} \epsilon^{-h^2 (E_a - E)^2} \tag{1}$$

in which h is a constant. If the area of one of the testing electrodes is A, we have $\frac{A}{dA}$ elements of area included between the electrodes, and the whole dielectric will fail at the weakest element of area. To estimate this dielectric strength, let

the area under the curve given by equation (1) be divided into $\frac{A}{dA}$ equal parts. Then the dielectric will most probably fail at the voltage represented by the center of the lowest section. This is near the boundary of the lowest section if the area is divided into $\frac{2A}{dA}$ equal parts.

The area under the probability curve included between the ordinate $(E_a - E)$ and the ordinate at negative infinity is given by the series

$$\text{area} = \frac{\epsilon^{-h^2(E_a - E)^2}}{2\sqrt{\pi}\, h\,(E_a - E)}\left[1 - \frac{1}{2\,h^2\,(E_a - E)^2} + \frac{1.3}{4\,h^4\,(E_a - E)^4} - \ldots\right], \quad (2)$$

and since the total area under the curve is unity, each member of equation (2) is equal to $\frac{dA}{2A}$. Therefore

$$A = \frac{\sqrt{\pi}\, h\,(E_a - E)\cdot dA \cdot \epsilon^{h^2 E_a^2}\,\epsilon^{-2h^2 E_a E}\,\epsilon^{h^2 E^2}}{1 - \frac{1}{2\,h^2\,(E_a - E)^2} + \frac{3}{4\,h^4\,(E_a - E)^2} - \ldots}, \quad (3)$$

Now if dA is decreased indefinitely, E_a becomes very large, so that E is small in comparison, and h becomes very small. In the limiting case, with dA infinitely small, equation (3) becomes much simplified, and the result is of the form

$$A = C_3\,\epsilon^{-C_4 E} \quad (4)$$

Solving for E,

$$E = \frac{1}{C_4}\log_e C_3 - \frac{1}{C_4}\log_e A = C_1 - C_2 \log_{10} A, \quad (5)$$

in which C_1, C_2, C_3, and C_4 are constants.

Equation (5) shows that the dielectric strength of thin insulating material should vary as a simple logarithmic function of the area of the testing electrodes when conditions are such that the effects of the edges of the electrodes are small. It is evident from equation (5) that if n separate tests of a given dielectric are made, using the same set of electrodes the difference between the average result and minimum result of the n tests

is most probably equal to $C_2 \log_{10} n$, this value being independent of the area of the electrode. It may also be shown that when n is large the average deviation of the individual results from their mean is approximately $0.43\ C_2$, no matter what the area of the testing electrodes.

The increased electric flux density which occurs near the edges of the electrodes causes the observed dielectric strength to be generally less than called for by equation (5), and this discrepancy is larger, the smaller the area of the electrodes, or the greater the thickness of the material under test. This is evident when it is considered that either decreasing the area of the electrodes or increasing the thickness of the dielectric increases the

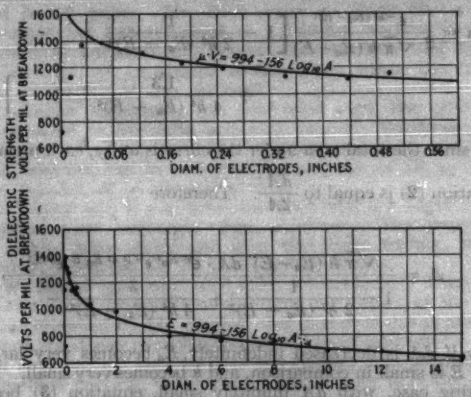


FIG. 4—EFFECT OF ELECTRODE AREA ON APPARENT DIELECTRIC STRENGTH OF VARNISHED CAMBRIC WHEN TESTED IN AIR, SHOWING AGREEMENT WITH THEORETICAL CURVE.

ratio of the maximum stress to the average stress, and also increases the proportion of the total area that is subjected to this maximum stress. When testing a single thickness of varnished cambric, relatively few of the failures occur near the edges of the electrodes; but when testing five or ten layers simultaneously, it will usually be found that a large proportion of the failures occur near the edges.

In order to illustrate the application of equation (5), the data given by Mr. Farmer for the dielectric strength of varnished cambric have been replotted (Fig. 4 herewith), and in the same figure has been drawn the curve

$$E = 994 - 156 \log_{10} A, \qquad (6)$$

the area being in square inches. The constants of this equation were determined by trial. The curve agrees very closely with the observed data when the diameter of the electrodes is 1/16 in. (1.588 mm.), or greater. When the diameter is less than 1/16 in. the effect of the edges predominates. The difference between the average and the minimum results of the tests with a given electrode should be 156 $\log_{10} n$, being the number of tests. When n is 10 this difference is 156 volts per mil at puncture; if n is 15 the difference is 183; if n is 21 the difference should be 206, etc. It will be observed that these differences as obtained from Table I of Mr. Farmer's paper are not greatly unlike the values given above.

The foregoing discussion indicates that the peculiar variation of the dielectric strength with the area of the testing electrodes is due mainly to irregularities of the material under test when the area of the electrodes is large, and to increased maximum flux density when the area is small. In deciding upon a size of electrodes to be adopted as standard, the area should be large if the aim of the tests is to determine the most representative value of the dielectric strength with the fewest number of tests. If, however, the most reliable result is desired while a minimum quantity of the material is used, a set of electrodes of small diameter should be chosen.

the area being in square inches. The conditions of this curve were determined by trial. The curve agrees very closely with the observed data, when the diameter of the electrodes is 1/16 in. (1.588 mm.), or greater. When the diameter is less than 1/16 in. the effect of the edges predominates. The difference between the average and the minimum results of the tests with a given electrode should be 150 volts, being the number of tests. When n is 10 the difference is 150 volts per cm. If n is 15 the difference is 250; if n is 21 the difference should be 300, etc. It will be observed that these differences as obtained from Table I of Mr. Forster's paper are not greatly unlike the values given above.

The foregoing discussion indicates that the peculiar variation of the dielectric strength with the area of the testing electrodes is due mainly to irregularities of the material under test when the area of the electrodes is large, and to increased maximum field density when the area is small. In deciding upon a size of electrodes to be adopted as standard, the area should be large if the aim of the tests is to determine the most representative value of the dielectric strength with the lowest number of tests. If, however, the most reliable result is desired with a minimum quantity of the material in hand, a set of electrodes of small diameter should be chosen.

Presented at the meeting of the Schenectady Section of the American Institute of Electrical Engineers, Schenectady, N. Y., December 16, 1913.

Copyright 1914. By A. I. E. E.

POWER FROM MERCURY VAPOR

BY W. L. R. EMMET

The theoretical limit of efficiency in a thermo-dynamic process is the ratio of the temperature range embraced by the process to the maximum absolute temperature used, $\frac{T-T_1}{T}$. In all processes available for commercial power development, the lower limit is fixed by the temperature of cooling water available, and is therefore not susceptible of variation. The possible upper limit is the temperature which can be produced by our fuel when burned with air, which in practise is about 2700 deg. fahr.

The purpose of the process here described is to utilize some of the energy available in ranges above that which can conveniently be utilized with steam. The theoretical efficiency of steam processes can be increased by using higher pressures, but since with rise of temperature the increase of pressure is very rapid, and since the steam turbine has limitations in the efficient use of high pressure, prospects of gain in this direction are not very attractive.

Mercury boils at 677 deg. fahr. at atmospheric pressure and condenses in a 28-in. (711-mm.) vacuum at 455 deg. fahr. It is therefore well adapted, at least by pressure and temperature conditions, for use in a temperature cycle above that now used with steam. Its use to increase greatly the temperature range available, and so to increase efficiency, is the object of the development here described.

Before going further, the writer desires to explain that the principle involved in this process was suggested to him by Mr.

Charles S. Bradley, who proposed and patented a quite similar process in which he intended to use certain other substances of high boiling point and relatively high vapor density. It has since been learned that there have been other proposals along similar lines, although none of them have involved the use of mercury. Consideration of the possibilities suggested by Mr. Bradley led the writer to study the characteristics of mercury, and from this study and a course of experimenting which has been going on for a year, the plans of procedure here shown and explained have been evolved. A set of apparatus suited to the production of about 100 h.p. has been nearly completed and it is hoped that experiments on a scale and of a character approaching commercial conditions may be made within a month or two. Anything so completely novel and so essentially complicated is naturally liable to delays, so that the prospect of successful tests cannot be confidently predicted. Since the process has been talked about and since a good deal of interest has been expressed, the writer has thought best to record his expectations and to make explanation of the plans which have so far been evolved.

In studying the thermodynamic possibilities of a substance like mercury, we proceed exactly as we do in the case of steam, and for the sake of convenience it may be well to give here some data relating to the subject.

Boiling point of mercury at atmospheric pressure	677 deg. fahr.	(358 deg. cent.)
Boiling point of mercury at 28-in. vacuum	457 deg. fahr.	(236 deg. cent.)

Vapor density is in the ratio of atomic weight and absolute temperature; as compared with water the vapor density of mercury is therefore 6.56 times as great at the boiling point and 6.8 times as great at 28-in. (711-mm.) vacuum.

Specific heat of mercury liquid	0.0373
" " " gas, (constant pressure)	0.0248

(According to Kurbatoff; *Zeit. Phys. Chem.* 43, 104, 1903).

Latent heat of vaporization—

at 25 lb. (11.3 kg.) abs.	r = 117	B.t.u.
" 15 " (6.8 kg.) "	r = 118	"
" 28-in. (711-mm.) vacuum	r = 121	"
" 29-in. (737 mm.) "	r = 121.5	"

(Calculated from formulas by Kurbatoff).

The boiling point of mercury at various pressures is shown by an accompanying curve, Fig. 1, and curves are also given in Fig. 2 showing the energy theoretically available from mercury vapor within various pressure ranges. These curves are calculated from Rankine's formula:

$$E = 778\left[Q_1 - Q_2\left(1 + \log.\frac{Q_1}{Q_2}\right) + \frac{x_1 r_1}{Q_1}(Q_1 - Q_2)\right]$$

E = energy in ft-lb.
Q_1 and Q_2 = heat of liquid.
x = dryness factor.
r = latent heat.

The data above stated may not have been as accurately determined as those which are available for steam calculations, but their substantial accuracy is indicated by the fact that in our experiments, the measured flow of vapor through nozzles has closely checked the calculations.

The method applied in this process may be stated briefly as follows: Mercury is vaporized in a boiler heated by a furnace of ordinary type. From this boiler (see Fig. 3) it passes at a pressure near or not much above the atmosphere, to the nozzles of a turbine which drives a generator or other utilizer of power. From this turbine it passes to a condensing boiler where it is condensed on the outer surface of tubes which contain water, and this water is vaporized by the heat delivered, and the steam produced is used to drive other turbines or for any other purpose. This condensing boiler is preferably placed at a level above the mercury boiler, so that the condensed liquid will run back into the mercury boiler by gravity without the aid of a pump. Since the mercury vapor is much hotter than the steam, the gases will normally leave the mercury boiler at higher temperatures than they have in leaving a steam boiler. To utilize this excess heat in the gases, it is proposed to convey them first, after leaving the mercury boiler, through a heater which raises the returning liquid almost to the boiling point, second, through a superheater which superheats the steam delivered by the condensing boiler, and third, through an economizer which heats the feed water for the condensing boiler and so reduces the gases to the lowest practicable flue temperature.

By careful study and experimental development, which will be later explained, means have been devised for reducing the amount of mercury used, for effectively preventing its loss or

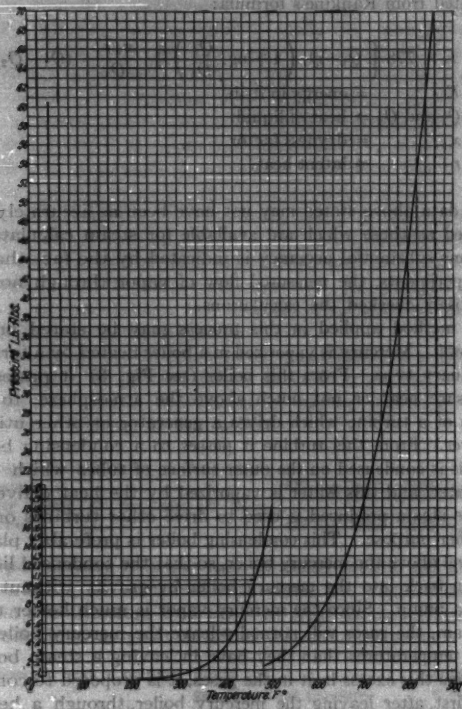


FIG. 1—CURVE SHOWING BOILING POINT OF MERCURY AT VARIOUS PRESSURES

dissipation, and for immediately detecting any failure in such prevention.

The disadvantages of mercury for such a process are: First, that it is very expensive, its cost being about 60 cents per lb.

($1.32 per kg.). Second, that it is poisonous and is capable of pervading the atmosphere in a very finely divided state in the neighborhood of places where the vapor can escape. Third, there are certain difficulties in confining both the vapor and the liquid, although these, with proper methods, are not serious.

Mercury's advantages as a thermodynamic fluid for the

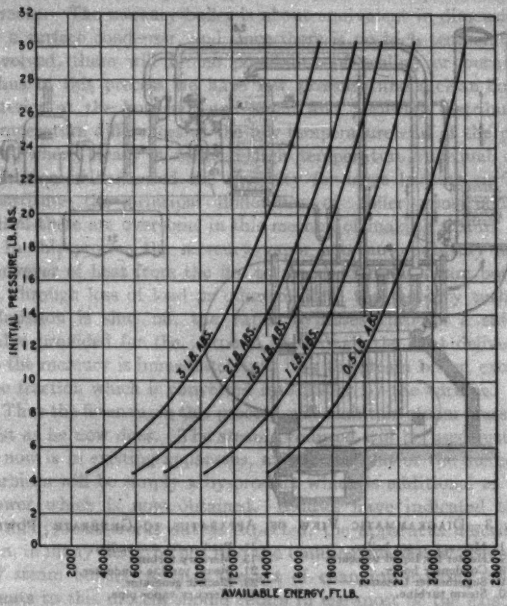


FIG. 2—ENERGY THEORETICALLY AVAILABLE FROM MERCURY VAPOR WITHIN VARIOUS PRESSURE RANGES

purposes desired are many. First: its boiling points at desired pressures are convenient. Second: its high specific gravity makes possible the use of gravity feed, sealing of valve stems, etc., and centrifugal sealing of turbine packings. Third: it is completely neutral, at the temperatures used, to air, water,

iron, and such organic substances as it may come in contact with. Fourth: it carries nothing in solution which can adhere to or affect heating surfaces, consequently the interior of boiler is always perfectly clean. Fifth: its vapor density is so high that it gives a very low spouting velocity, and consequently a very simple type of turbine can be used. Sixth: it does not wet the surface of turbine blades and consequently gives ap-

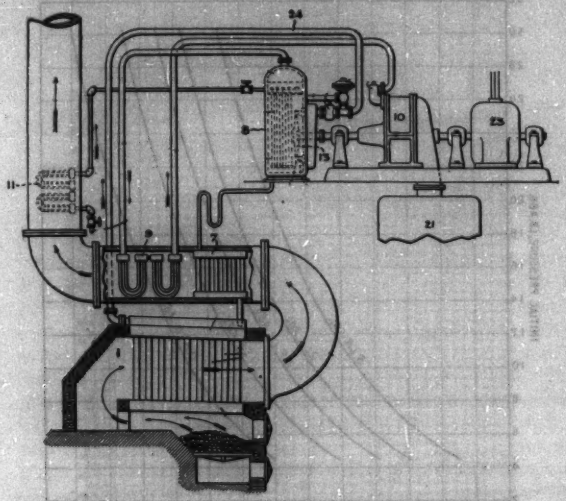


FIG. 3—DIAGRAMMATIC VIEW OF APPARATUS TO GENERATE POWER

1. Mercury vapor boiler.
7. Heater for liquid mercury.
8. Condenser boiler.
9. Superheater (steam).
10. Steam turbine.
11. Feed water economizer.
13. Mercury turbine.
21. Steam turbine condenser.
23. Electric generator.
24. Mercury vapor pipe.

parently no erosion. It is believed that the action between the vapor with its accompanying liquid and the blade surface will conduce to a high economy in a turbine, although no positive data on this subject have yet been obtained. Seventh: Its volume at convenient condensing temperatures is such that it can be used in turbines without excessive bucket heights. One of the greatest limits of design in steam turbines is the large

area required for the efficient discharge of the low-pressure steam. With mercury vapor, this difficulty does not exist. Eighth: delivering its heat at the temperature and in the manner which it does, the condensing boiler in which this heat is used to make steam is very small and simple as compared with a steam boiler. Steam boilers transmit an average of about 6 watts per sq. in. (6.45 sq. cm.) with an average temperature difference of about 1100 deg. fahr. A surface condenser transmits 18 watts per sq. in. with 20 deg. fahr. temperature difference. The mercury boiler is about equivalent in dimensions to a surface condenser, and since there is no high temperature involved, there will be no possibility of scaling or burning. Thus in this process we have low pressure and a clean boiler interior at the hot end, and small and perfectly distributed temperature differences at the low-temperature end of the process, where steam is made. High temperature, unequal distribution of heat, and the necessity for large heating surface constitute the principal difficulties of boiler construction. All of these are overcome in this method of making steam.

In this process the mercury vapor acts automatically as a conveyer of heat from the fire to the condensing steam boiler. If, through loss of load or other reasons, the mercury turbine admission is shut off, the vapor bypasses through a safety valve provided for the purpose, so that all the heat delivered to the mercury is immediately put into the steam boiler, except the fraction which is converted into power by the turbine.

Thus the fireman, in this process, will maintain steam pressure just as he now does. The steam produced will be used just as it now is in existing apparatus, and the output of the mercury turbines will be simply a by-product which is additional to the power which is now obtained. Studies have indicated that if this process works out as expected, the apparatus described can, in many cases, be put into the building space now occupied by steam boilers, so that the act of changing existing steam plants to this process should retain in use most of the existing investment.

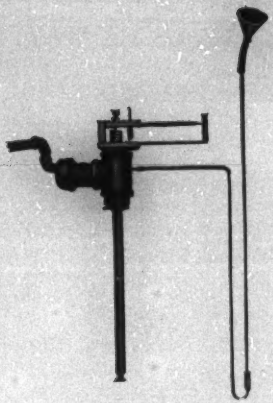
Before entering into the details of experiments or of the methods by which it is hoped to accomplish these results, it may be well to state the degrees of economy which should be accomplished if this development succeeds. Assuming heat deliveries to surfaces exposed equal to those in steam boilers under

equivalent conditions of temperature difference, gas velocity, and radiation, and assuming a turbine efficiency equal to that of steam under equivalent velocity conditions, the calculation shows that in an efficient modern power station, the same amount of steam can be delivered to the turbines at the same superheat, thus giving the same turbine output, and that in addition about 66 per cent of the power so delivered can be delivered by mercury turbines, the fuel required being only about 15 per cent greater than that which would be used with the steam alone. Thus the gain in capacity of an existing station would be approximately 66 per cent and the gain of output per pound of fuel would be about 44 per cent. This calculation is based upon a mercury vapor pressure 10 lb. (4.5 kg.) above the atmosphere and a vacuum of 28.5 in. (724 mm.) at the steam turbine outlet.

About 10 lb. (4.5 kg.) of mercury would be evaporated for each pound of steam produced, the steam pressure being about 175 lb. (80 kg.) gage, superheat 150 deg. fahr., and the final temperature after gas leaves economizer being about 300 deg. fahr. The vacuum in both steam and mercury turbines can be maintained by the same air pump, means being employed to separate all mercury vapor from the air in a suitable cooler.

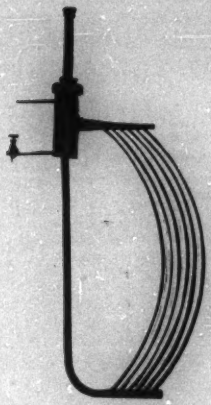
A non-condensing steam plant produces more than half as much power from a pound of fuel as a good condensing station, and since the mercury process can be superimposed upon a non-condensing steam process as well as upon a condensing steam process, it is obvious that with the mercury combination the non-condensing plant can be made almost as economical as the best existing condensing plants. It is also obvious that when the mercury process is added in cases where steam is less economically used than in modern power stations, the gain will be relatively greater. The purpose of the process is to replace steam boilers wherever they are used and to obtain power from mercury turbines as a by-product.

Experimental data indicate that not more than $10 worth of liquid mercury per kilowatt output of mercury turbine will be required for such a process, and it is probable that with suitable arrangements, this amount can be considerably reduced. The general application of such a process would require immense quantities of mercury, but inquiry has indicated that the sources of supply are such that the largest conceivable de-



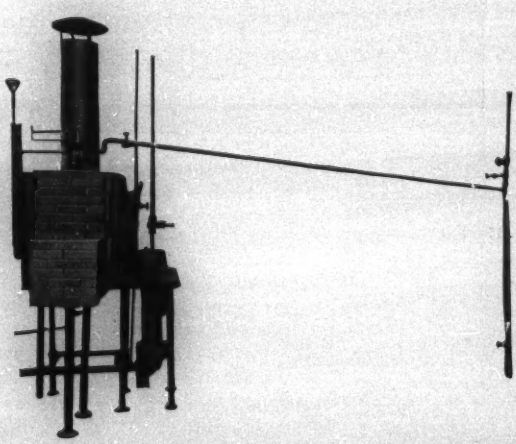
[EMMET]

FIG. 4
FIRST EXPERIMENTAL MERCURY BOILER TUBE



[EMMET]

FIG. 6
SECOND EXPERIMENTAL MERCURY BOILER TUBE



[EMMET]

FIG. 5—MERCURY BOILER TUBE OF FIG 4, ENCASED IN BRICK SETTING

[EMMET]

FIG. 11—MERCURY BOILER AND TURBINE AS ERECTED IN POWER HOUSE

mand for such a purpose would not permanently increase the price.

In the experimental calculations of this process which have so far been made, the vapor has been produced in heating elements similiar to those proposed for an actual boiler under the most severe condition of heat delivery by gas flow and radiation. The vapor has been carried from such boiler elements to a nozzle and this nozzle has been exhausted into a condenser from which the liquid is drained back into the boiler by gravity, the vacuum being maintained in the condenser by an air pump. In this experiment the only element lacking is the turbine wheel, which, although it constitutes the only visible evidence of results in such a process, is in reality unimportant, since the nozzle is the real engine which transforms heat into motion, the movement of the wheel by the moving fluid being a mechanical matter governed by laws which are very well understood.

In these experiments, pressures and amounts of liquid condensed were measured, and these measurements show that the flow of vapor through the nozzle was in agreement with the calculations from the data above stated.

In all the tests which have been made with these experimental elements, there has not been a trace of chemical action upon the mercury or steel, although air, water, oil, and various kinds of dirt have been present in considerable quantities, and although very extreme temperatures have at times been used.

Investigation of the conditions of heat transference and circulation in the production of mercury vapor has involved much labor in study and experimenting, and through this work certain data have been collected which, in combination with known data concerning action in different parts of steam boilers, have been applied to the design of a boiler of considerable size, which is now nearly completed. This boiler would appear to be the only part of the process which involves any difficulty, and it is hardly fair to expect that it will be in every respect satisfactory or in accordance with calculations, although the evidences in its favor seem to be very strong, and although every detail which enters into it has been the subject of successful experimenting. It is believed, however, that any difficulties which may arise can be corrected and that this process is practicable for approximately such results as have been stated.

A turbine of suitable design has also been produced, and a condensing boiler, with all the auxiliary apparatus necessary for the trial of the process as it might be applied commercially.

With a view to developing a design for a mercury boiler which would produce the vapor with the practicable methods of firing without destructive temperatures in the steel and with a small total amount of mercury in use, it has been necessary to do much experimenting to determine the behavior of mercury under boiler conditions. The first experiments made were with tubes containing solid cores with a small clearance between the core and the tube, and a central hole in the core provided for circulation of the liquid. The apparatus used in this experiment is shown by Fig. 4. A rod was carried downward through the central duct and projected out through a packing as shown. The relative expansion of this rod and of the outer walls of the tube was indicated by a multiplying lever as shown, which afforded an accurate measure of average temperature difference between the outer walls, which constitute the heating surface, and the liquid which was flowing in contact with the rod. This tube was subjected to various heating conditions and curves were plotted which compared rates of vapor flow with temperature difference. Some unexpected results were encountered, and the nature of the action was investigated by boiling mercury in concentric glass tubes having an annular clearance about equivalent to that used in the steel tubes. These experiments showed that to absorb a large amount of heat with a small temperature difference between the heated surface and the liquid, it was necessary to provide for a very free circulation of the liquid so that a large amount of liquid could flow. The size of the central hole had a very positive effect upon the vapor capacity of the tube. Since the mercury does not wet the heating surfaces, the tendency is for the vapor to fill the space between the liquid and the heating surface and thus to prevent heat removal. The way to get effective action in a mercury boiler is to create conditions by which so much liquid will circulate in hot parts that very little vapor is formed until the heated liquid reaches the upper parts of the tubes where the pressure is relieved, and where the heat stored begins to be released in vapor.

Difficulties with temperature differences are only encountered in the hottest parts of the boiler where radiation plays an im-

portant part. With the low rates of heat transference which prevail through a greater part of the surface, extremely narrow spaces can be provided for the circulation of liquid and for the release of the vapor which is formed.

Having obtained, by experiments, data concerning possible rates of heat transference, a boiler was built in which the heating surface was made up of round tubes with concentric cores. The tubes were expanded into a horizontal sheet which formed the bottom of a box, and arrangements were made by which the central ducts in cores always received a supply of liquid. The tubes in this boiler were rather thin, and in experimenting with it, it was found that at the hot end the expanded joints in the tube sheet became loose, the temperature differences imposing strains which exceeded the elastic limit of the metal. This trouble could have been corrected by acetylene-welding these joints, but this would have involved various changes and difficulties, and since trouble was also encountered in making the bolted joints of the box vacuum tight, it was decided to abandon this boiler and build another on an entirely different principle, which had been in the meantime devised and experimented with. The construction of this new boiler is shown by Fig. 7 and the experimental unit used to determine its characteristics is shown by Fig. 6.

This boiler is made up of a number of heating units, each consisting of an upper and a lower header which are connected together by curved flattened tubes. The flattening is to reduce the space which must be filled with liquid mercury without diminishing the surface. The curvature is to prevent mechanical strains through inequal expansion caused by irregular heating. These flattened tubes are connected into the headers by acetylene-welded joints. The tubes are first welded from the inside into channel-shaped pieces; these channels with the set of tubes connecting them are then annealed so as to release all strains incident to the welding. After annealing, they are tested with high-pressure air, suitable clamps being used to confine the air in the channels. If the welded sheets will stand the anneal and the subsequent pressure test, it is assumed that they will be reliable for service, since in service they will be subject to uniform temperature conditions and will be practically free from mechanical strains. These channel pieces are then welded to steel headers so that the whole unit becomes perfectly tight and capable of standing a high pressure. The

headers of these units terminate, as shown, in taper nozzles, which fit into taper holes in the bus header at the bottom and into a vapor chest at the top. A curved liquid duct connects the vapor chest to the bottom header at the hot end so that

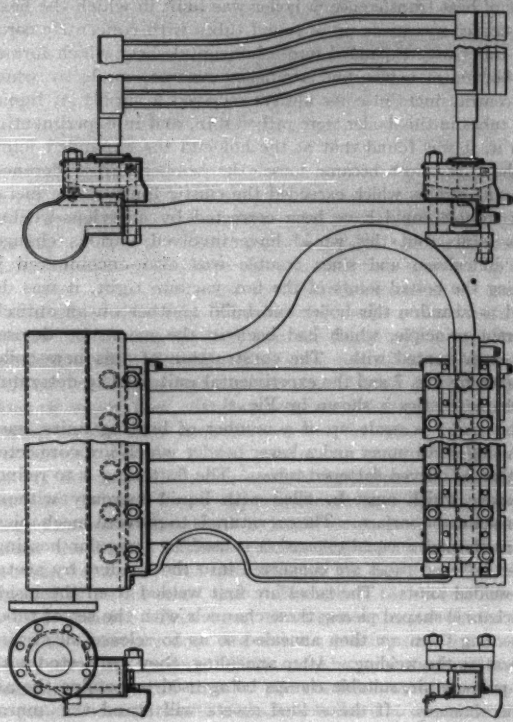


Fig. 7—Assembly of Experimental Mercury Boiler

the heating units which are exposed to the greatest heat receive the most direct supply of liquid. In these hot units, a larger internal space will be allowed than in the units which occupy the cold part of the boiler, so that the colder part will not carry an unnecessary amount of liquid.

If these heating units will remain tight, and the success of experiments indicates that they will, it will be impossible for liquid mercury or vapor to escape except at the joints where

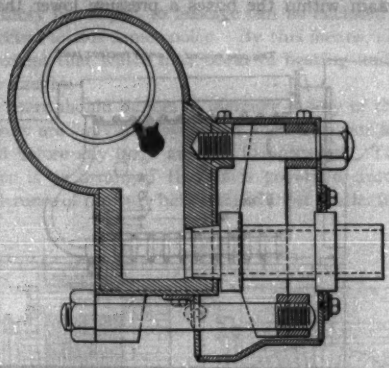


FIG. 8—SECTIONAL VIEW OF UPPER MAIN HEADER, MERCURY BOILER

these headers connect to the bus headers and to the vapor chest, or at the joints through which the vapor is conveyed to the turbine. To guard against loss through leakage in such places, arrangements have been made, as shown in Figs. 8 and 9, by

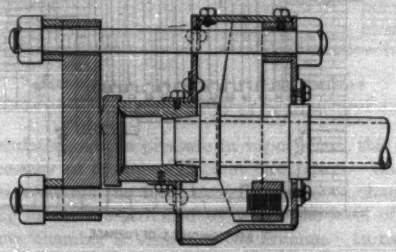


FIG. 9—SECTIONAL VIEW OF LOWER MAIN HEADER, MERCURY BOILER

which the sets of joints at the top and bottom of the boiler are enclosed in boxes which are practically air-tight, the bolts used in tightening these joints extending outside of the boxes in such a manner that a leaky joint can be drawn up. These boxes

are connected by ducts to a condensing cooler in which low pressure is maintained by suction from the base of the stack or from any other sufficiently exhausted place. This suction will maintain within the boxes a pressure lower than any of

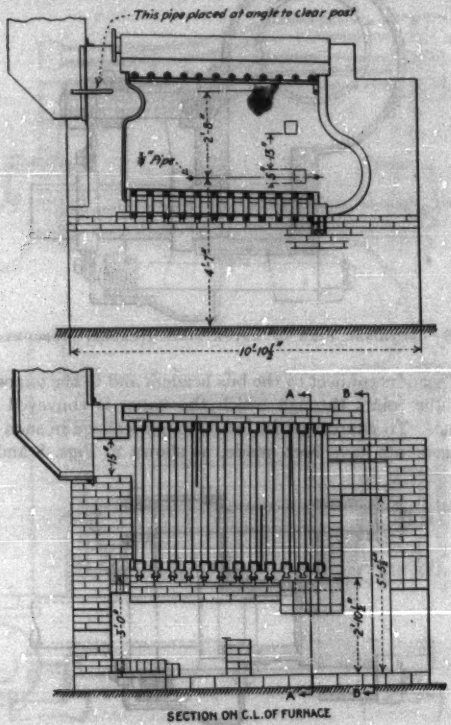


FIG. 10—MERCURY BOILER SETTING

the pressures which surround them, so that there will be a constant indraft of air through such leaks as may exist and a flow of all liquid or vapor which may escape, into the cooler, where it will be carried through passages over water pipes until all

the vapor is condensed and nothing but cool air and gas is discharged. In a similar manner, any joints in the system which might possibly be subject to leakage can be enclosed by boxes and connected to this same cooler. By this means, all possible leakage, except that which may occur in heating units, will be effectively caught.

In case there should be loss of mercury in any of the heating units, means are provided by which such loss can be quickly discovered before any large amount has escaped. The feed of each boiler is so arranged that it is governed automatically by the difference of pressure between the lower header from which

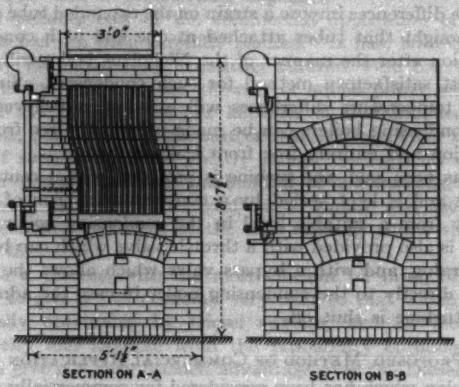


FIG. 10A—SECTIONS OF MERCURY BOILER SETTING SHOWN IN FIG. 10

liquid circulates and the pressure in vapor chest, this being the force necessary to produce sufficient circulation. Back of the valve which admits the feed, there is a reserve chamber, and connecting means are provided by which the level of liquid in this reserve chamber is visible to the fireman. In case loss of this liquid is apparent, the doors would be opened, the fire drawn, and the liquid drained out of the boiler into a receiving tank. The boiler can then be tested with air pressure and the leaky elements can be replaced, the construction being such that any one of these elements can be taken out without disturbing the others.

The arrangements of the turbine have also been improved as

the result of experience. The first turbine arranged was made from an old experimental steam turbine and had many joints which were difficult to keep vacuum-tight. The new experimental turbine has only one joint, arranged in a manner which has been experimented with and which will avoid leakage.

The condensing boiler used in the experiment now in preparation is made from a standard high-pressure feed heater having a water space at the top and bottom connected by tubes in the manner customarily used in such devices. This boiler has apparently worked satisfactorily and produced steam from mercury vapor in the manner expected. It is not, however, considered a suitable design for the purpose, since the temperature differences impose a strain on the expanded tube sheets, It is thought that tubes attached at one end with concentric circulation after the manner of the Nicholaus boiler will afford the most satisfactory method for such condensers. Since no violent temperature differences will exist, it is believed that these condensing boilers can be made practically free from deterioration and entirely free from leakage.

As has been said, the turbine is provided with a centrifugal packing and is kept sealed by a constant admission of liquid mercury from a suitable level in the condensing boiler. The turbine is also provided with a throttle valve which can be used in governing, and with a bypass valve which allows the vapor to pass directly to the condensing boiler in case the admission to the turbine is shut off.

Proposed Method of Commercial Application

The plan which has been considered for commercially applying this process is to produce a simple type of unit suitable for installation in the same floor space occupied by a standard 500-h.p. steam boiler. This unit would be so proportioned that the steam output of the condensing boiler would equal that obtainable from the standard 500-h.p. boiler. For each of these boiler units, a separate turbine and generator would be provided, the nature of this process being such that there is no loss of efficiency involved in such multiplication of generating units.

Since it would never be desirable to operate these mercury-driven generating units alone, the generators could be made either of the induction or synchronous type, completely enclosed, with an air supply from some clean outside source.

Their circuits would run to the main switchboard, they would need no attendance, and the space around them would not have to be kept either cool or clean, although it would generally be possible to get them within an enclosure which would not be exposed to the fire-room dirt. By such means a single set of parts or combinations of a few standard parts could be made to cover a very wide demand, and this would greatly simplify the commercial introduction of such a process.

Without the acetylene welding process, a satisfactory mercury boiler design would be very much more difficult to arrive at. The manufacture of such boilers as are here described would involve a very large amount of acetylene welding, requiring great care and a considerable expense.

The possible cost of the commercial application of such a process has not been carefully studied. It has, however, been roughly estimated that if existing stations were converted to this method, the cost per kilowatt of added power would not exceed the present cost per kilowatt of well-designed steam stations, not including the cost of real estate. Thus this process, if successful, would greatly extend the capacity of existing stations and postpone the building of new stations, the saving would about cover the real estate values, and the gain in fuel economy over that of the best existing plants should be about 45 per cent.

Such a process, with the most efficient oil firing of boilers, ought to give a fuel economy very near to that which is commercially obtainable by Diesel engines, and its mechanical simplicity and freedom from the probability of deterioration should give it a very decided advantage over the Diesel engine. While it is not wise to make definite predictions about anything so radically new, it certainly appears to the writer that this process is worthy of very careful study.

THE I. E. C. MEETING AT BERLIN

Advance Report to the U. S. National Committee on the Berlin Meeting of the International Electrotechnical Commission

The following report is intended to outline the results attained at the recent meeting of the I. E. C., in Berlin, (September 1st to 6th, 1913) for the information of the U. S. committee-members, in advance of official reports from the General Secretary of the Commission, with respect to which official reports, this preliminary statement must of course be subordinate, and subject to amendment in detail.

The Berlin meeting was the fifth meeting which the I. E. C. has held; but it was the second plenary meeting, since three of the meetings have been of semi-official character only. It was well attended, since 24 nations were represented by some 70 delegates, all told. It was the first meeting held in Germany, and the German Government was represented by President Dr. E. Warburg of the Physikalisch-Techniche Reichsanstalt, Geheimrat Dr. K. Stecker, Dr. Jaeger, and others.

In the absence of the President of the I. E. C., Dr. Budde, who was unfortunately prevented by illness from attending, Dr. Warburg presided at the official opening on September 1st. An address of welcome was read by Dr. Lewald, the Director of the German Ministry of the Interior. The address was responded to by Prof. Paul Janet of the Laboratoire Centrale de Paris. Mr. Alexander Siemens presided at the official closing meeting.

The sessions of the Commission at Berlin were of four kinds; namely (1) official plenary meetings of formal opening and final ratification, (2) international sub-committee meetings on special subjects on the 1st and 2nd Sept., where the hardest work, was, naturally, undertaken; (3) unofficial or working meet-

ings, on 3rd and 4th Sept., at which the sub-committee reports were presented to the main body, discussed, and acted upon; and (4) a final Council meeting for the election of officers for the ensuing term, and other formal administrative business.

There were four international sub-committees appointed at Turin in 1911, two of which had been in existence prior to the Turin meeting; these committees were constituted and convened as follows:

Subject	Members, one from	Dates of Meeting	Places of Meeting	Chairman at Berlin
Nomenclature	France Germany Great Britain	March, 1912 March, 1913 September, 1913	Paris Cologne Berlin	Prof. S. P. Thompson
Symbols	Belgium France Germany Great Britain Italy Sweden Switzerland United States	March, 1912 January, 1913 September, 1913	Paris Zürich Berlin	Geh. Dr. K. Strecker
Rating of Electrical Machinery	Belgium France Germany Great Britain Italy Sweden Switzerland United States	May, 1912 January, 1913 September, 1913	Paris Zürich Berlin	Herr Huber-Stockar
Prime movers in connection with Electrical Plant	Austria France Germany Great Britain Italy Norway Spain Sweden Switzerland United States	January, 1913 September, 1913	Zürich Berlin	Dr. H. Zoelly

Nomenclature. The committee on Nomenclature presented an excellent report, which was adopted at the plenary meeting. It contained some 80 electrotechnical terms and definitions, in English and French. The list is too long to be presented in this outline report.

Symbols. The committee on Symbols submitted a report,

in French, which was adopted at the plenary meeting. An English rendering is appended hereto as Appendix A. It will be seen that symbols have been internationally agreed upon for 36 quantities. In cases of nearly half of them, however, (16), agreement could not be reached upon a single symbol; so that for these an alternative is offered. Designating letters, or letter-groups, are provided for 15 electrical units in common use. Standard abbreviations for 29 metric units are also agreed upon. Seven common mathematical symbols are recorded, including both i and j for $\sqrt{-1}$, according to the preference of the writer.

Rating. The committee on Rating was confronted with an exceptionally heavy task. This committee held meetings in Paris in 1912 and in Zurich in 1913. It published its work at those meetings under I. E. C. Publications Nos. 17 and 20. Moreover, General Secretary leMaistre, in I. E. C. Publication 9, of August, 1911, presented the electric machinery rating rules of various countries in a form adapted to comprehensive comparison. Yet in spite of all this preliminary work, it was found that essential issues leading to an international rating for such machinery had not been clearly formulated when the Rating committee met in Berlin. In fact, considering our own committee alone, it is debatable whether a satisfactory technical basis for the rating of electrical machinery had been reached in America prior to the Midwinter Convention of the A. I. E. E., held under the auspices of its Standards Committee, in February, 1913. Consequently, the fact that complete international agreement upon international rating rules was not reached at Berlin need not occasion great surprise.

Just before the Berlin convention of the I. E. C., the U. S. delegation had the advantage of meeting with a Section of the Engineering Standards Committee of Great Britain, which included the British delegation—in London on Aug. 23rd, and again in Berlin, on Aug. 31st. At these meetings the viewpoints of the British and American committees were carefully compared, and adjusted into uniformity on many matters relating to international rating. In effecting this valuable parallelisation of technical views between the two committees, Mr. H. M. Hobart of our committee rendered signal service. The complete conformity between the views of these two national committees on the points of immediate importance in Rating was probably helpful to the I. E. C. International Committee on Rating, in reaching a clear determination of the extent to which

international opinion was in agreement or disagreement, thus paving the way for reaching a final agreement at some future convention, let us hope at San Francisco.

Complete agreement was reached in the I. E. C. Rating Committee on the principle of defining the rating of an electrical machine, so far as thermal behavior is concerned, by a limiting internal or "hottest spot" temperature, as judged by a definitely lower maximum measured temperature attained in the apparatus. A list of such maximum permissible measured temperatures for certain different classes of insulation was agreed on for machines up to four kv. in e.m.f. In order, therefore, to fix upon the international rating, it was only necessary to settle upon an internationally conventional reference-temperature, or circumambient room-temperature. Thus, in the case of impregnated cotton windings, up to four kv., the maximum permissible measured temperature was set at 90 deg. cent. If the international reference temperature, or initial ambient temperature, is taken as say 40 deg. cent., then it follows that the international rating of a machine for continuous service is that output which will finally bring the measured accessible temperature from 40 deg. to 90 deg. cent., or will establish a temperature rise of 50 deg. cent. When working at an actual ambient temperature of 40 deg. cent., the available output would be the same as the international rating. When working at an actual ambient temperature of say 30 deg. cent., the available output would be greater than the international rating, roughly in the ratio $(60/50)^{\frac{1}{2}}$ or say 1.13; whereas, when working at an actual ambient temperature of say 50 deg. cent., assuming that the shunt windings of the machine could be operated at so high a temperature, the available output would be less than the international rating, roughly in the ratio $(40/50)^{\frac{1}{2}}$, or the machine would have to be derated about 16 per cent. The advantage of selecting a fairly high international ambient temperature is that the number of localities will be reduced in which, by reason of climatic or locally developed high temperatures, the machine must be derated, or the purchaser warned against taking from it an output equal to its international rating. On the other hand, a fairly low international ambient temperature has the advantage of increasing the international rating of a given machine. That is, a fairly high international ambient temperature makes for safety in applying a load equal to the rating, under summer conditions of service, but tends to diminish the rating.

It is only reasonable to expect that cool countries, lying on the anti-torrid sides of the temperate zones, should desire to set their local or national ambient temperatures correspondingly low, so as to avail themselves of the full benefit of greater available output that their cool climates permit, and that such countries should prefer to have the international ambient temperature set at the same level, so as to have the same rating internationally as locally; even if the machines have frequently to be derated in warmer climates or in engine rooms. So too, it is likewise reasonable to expect that countries subject to warm weather in summer should prefer to have a higher and safer ambient temperature in their local or national standardization rules, in order to avoid frequent derating.

It was found that the great majority of the delegates at the Berlin meeting favored 40 deg. cent. for the ambient temperature of reference, as recommended at the A.I.E.E. midwinter convention, with an international continuous rating for machines of impregnated cotton winding corresponding to 50 deg. cent. rise. But two countries of northern Europe held out for 35 deg. cent. ambient temperature, and therefore a rating based on 55 deg. cent. rise. The delegates from those countries intimated that the 50 deg. cent. rise rating, as recommended for the A. I. E. E. Standardization Rules, was over-conservative, and that a rating based on 55 deg. cent. rise, or nearly 10 per cent more, was safe and proper. The 50-deg. cent.-rise delegates maintained, on the other hand, that the majority of places in the habitable world, where dynamo-electric machinery was operated, were subject to distinctly higher summer ambient temperatures than 35 deg. cent.; so that it was to the interest of international electrical engineering that the international rating should be kept down to a conservative value, in order to minimize the need for summer derating, or precautions against summer overheating under international rating load. No agreement could therefore be reached, and the question of ambient reference temperatures was referred back to the various national committees for further consideration.

On all other points of immediate importance to continuous rating, agreement was reached. Thus, it was admitted that overloads should not be recognized in international rating; *i.e.*, that an international rating for continuous service should specify one maximum permissible output only, and recognize no extras; although it would manifestly lie within the province

of an operating engineer to increase the load above the international rating load in winter time, or under any conditions when the temperatures attained in the machine were well below the specified maximum permissible limits. As soon, therefore, as an international ambient temperature can be agreed upon, international rating of the great majority of machines will thereby be immediately determined. At the present time, however, it is manifest that one and the same machine is subject to different ratings in different countries; or, in other words, that different countries rate their machines in a materially different way.

The report of the I.E.C. Rating Committee, shorn of all specifications as to international ambient temperature, or as to temperature rise for the international rating, was then adopted by the plenary meeting, and will doubtless be issued by the Central office in due course. The list of maximum permissible measured temperatures appears in Appendix B herewith.

Prime Movers. The committee on Prime Movers presented an excellent report dealing mainly with the definitions and nomenclature of hydroelectric installations. This report was also adopted by the plenary meeting, and may be expected to appear later in the official proceedings of the Berlin Meeting.

Annealed Copper Standard. The subject of an International Standard of Annealed Copper was also dealt with at the convention. It will be remembered that the Bureau of Standards, at the request of the A. I. E. E. Standards Committee, took up, in 1910, the computation of a new Standard Copper Wire Table; because recent investigations had shown that the temperature coefficient of resistivity employed in the old Institute Copper Wire Table, computed by the Standards Committee in 1893 from Matthiessen's data, was inaccurate. The Bureau undertook the task,* and made an extensive preliminary investigation of both the resistivity and the resistivity temperature-coefficient of copper wire employed industrially in America. The Bureau found that the mean value of resistivity of good annealed industrial copper in the United States, expressed in terms of the meter-gram, or resistance of a wire one meter long weighing one gram, was, at 20 deg. cent., nearly 0.153 ohm; whereas Matthiessen's standard, as interpreted in the A. I. E. E. TRANS-

*See Circular No. 31 of the Bureau of Standards, "Copper Wire Tables", 2nd Edition, January 1, 1914.

ACTIONS, was represented by a meter-gram of 0.15302 ohm at 20 deg. cent. Consequently, the Bureau accepted the meter-gram of 0.15302 international ohm at 20 deg. cent. as the annealed copper standard, with a temperature-coefficient of 0.00393 per deg. cent. from and at 20 deg. cent. In 1911, the Bureau prepared to issue new wire tables based on the above values. When, however, these data were presented to electrical engineers in Europe, with a view to arriving at an international agreement on the electrical properties of standard annealed copper wire, small differences in data among the various countries revealed themselves. A proposal was then made, in Germany, to adopt a standard copper conductivity as represented by a conductance of 58.00 mhos in an annealed copper wire, at 20 deg. cent., having a length of one meter and a cross-section of one sq. mm. Such a standard corresponds to a meter-gram of 0.15328 ohm at 20 deg. cent. This proposal met with general favor among the National Physical Laboratories, was endorsed by the Bureau of Standards in 1912, approved by the Standards committees of the A. I. E. E. and the A. S. F. T. M. in 1912, recommended by the Rating committee of the I. E. C. in 1912, was finally agreed to, in the French text, by representatives of the National Physical Laboratories in Berlin last September, and was forthwith adopted by the plenary meeting of the I. E. C. A translation into English of the French text appears in Appendix C, herewith.

The adoption of one and the same electrical standard resistivity and temperature-coefficient by the National Laboratories of France, Germany, Great Britain and the United States, as well as by the I. E. C. at Berlin, should ensure complete agreement between the future standard copper-wire tables in all parts of the world, on a conductivity basis substantially the same as Matthiessen's standard. In fact, the differences which have existed during the last few years between the electrical copper standards of the different countries have been unimportant commercially; but have yet been sufficiently large to confuse their numerical comparison. By the action at Berlin, these small numerical discrepancies should in future disappear.

At the Council meeting which followed the plenary meeting, M. Maurice Leblanc, of Paris, was unanimously elected as the President of the I. E. C., to succeed Dr. Budde. It is expected, therefore, that he will preside at the next meeting, at San Francisco, in 1915. Col. Crompton was also unanimously re-elected as Honorary Secretary.

An important decision was arrived at in the Council meeting, to the effect that the French text shall henceforward be considered as the text of reference, and that all other texts shall be considered as translations therefrom. French is more familiar to the delegates at large than any other single language, and the difficulty of maintaining two official records side by side in different languages is very great. They can never be brought into such exact equivalence that reference to each, in case of minutious enquiry, will give exactly the same result. Moreover, by having a single reference language, opportunity is opened for adding, in future, other admitted languages of the Commission to the printed records, at owners' risk and expense, thereby extending the literary usefulness of the Commission's publications.

The Spanish delegates invited the Special committees to hold the next meeting in Madrid, and this will probably take place next April. Prof. Chatelain, the Russian delegate, on behalf of his committee, officially invited the I. E. C. to hold a plenary meeting, in 1917, at St. Petersburg.

The German committee, in view of the large amount of work to be done at the meeting, very considerately refrained from overtaxing the delegates with social engagements. The entertainments they offered, were, however, excellent in character, and were greatly appreciated.

The U. S. delegates attending the meeting were President C. O. Mailloux, and Messrs. Bell, Hobart, Kennelly and Sharp. Mr. Mailloux was elected the President of the unofficial meetings, where the duties devolving on the presiding officer are numerous and exacting.

At the plenary meeting, President Mailloux, in pursuance of the invitation given in the first instance by President Dunn at Turin, extended a cordial invitation on the part of the A. I. E. E. and the American Committee, to hold a meeting of the I. E. C., and an International Electrical Congress, at San Francisco, in 1915. This invitation has already been accepted, and we may hope that a large and representative meeting will be held there the year after next.

Respectfully submitted,

A. E. KENNELLY

Secretary U. S. Committee.

APPENDIX A

An English rendering of the Report of the Special Committee on Symbols adopted in French at the Berlin plenary meeting of the I. E. C.

General Remarks

By confining oneself to Electrotechnics alone, it would seem possible to standardize symbols. The following rules may serve as a guide to the attainment of this object:

The symbols must be clearly distinguishable one from another when writing with a pen on paper, with chalk on a blackboard, and with a typewriter. In the printed text, it is advisable to use a different type for the symbols from that of the text. It is desirable that in ordinary handwriting, one should not be obliged to add distinctive signs to symbols to specify the type to be employed. It should be possible to spell out the symbols when writing them on the blackboard. Finally, preference should be given to those symbols already in common use. From this it will be seen that it is impossible to make a distinction, in ordinary handwriting, between Roman letters and Italics, and that small roundhand letters, being too difficult to differentiate from the above, cannot be used. It is generally agreed to abandon Gothic type, as requiring too long a time in writing. Finally, many of the Greek capitals are identical with Roman capitals. Taking the above points into account, there remain about one hundred symbols available in Roman, Script and Greek type, of which several are already used for mathematical symbols and which are necessary for the purposes of the electrician. A list of symbols most frequently needed in electrotechnics is appended herewith. Taking into account certain symbols which are occasionally made use of, it is obvious that there will be none left for purely physical or mechanical quantities. Thus one may have, in the same formula, electrotechnical symbols as well as others used in mechanics and physics generally; this is especially the case in equations containing mass, moment of inertia, speed, density, temperature, quantity of heat, etc. The Special Committee on Symbols suggests, therefore, that in such cases, for physical and mechanical quantities, the symbol habitually used by physicists and mechanical engineers should be employed, if this symbol does not already exist in the formula as an electrotechnical symbol. If, on the contrary, it already exists in the formula, it is desirable that it be accompanied by a distinctive sign or that the notation be changed.

Special Propositions

RULES FOR QUANTITIES

(*a*) Instantaneous values of electrical quantities which vary with the time to be represented by small letters. In case of ambiguity, they may be followed by the subscript "t".

(*b*) Virtual or constant values of electrical quantities to be represented by capital letters.

(*c*) Maximum values of periodic electrical and magnetic quantities to be represented by capital letters followed by the subscript "m."

(*d*) In cases where it is desirable to distinguish magnetic quantities (constant or variable) from electric quantities, magnetic quantities should be represented by capital letters of either script, heavy-faced, or other special type. Script letters should not be used except for magnetic quantities.

(*e*) Angles should be represented by small Greek letters.

(*f*) Dimensionless and specific quantities should be represented wherever possible by small Greek letters.

1. Ordinary numerals as exponentials shall exclusively be used to represent powers. (In consequence, it is desirable that the expression $\sin^{-1} x$, $\tan^{-1} x$, employed in certain countries, be expressed by arc sin x, arc tan x.)

2. The comma and the full-stop shall be employed according to the custom of the country, but the separation between any three digits constituting a whole number shall be indicated by a space and not by a full-stop or a comma (1 000 000).

3. For the multiplication of numbers and geometric quantities, indicated by two letters, it is recommended to use the sign $\times$, and the full-stop only when there is no possible ambiguity.

4. To indicate division in a formula, it is recommended that the horizontal bar and the colon be employed. Nevertheless the oblique line may be used when there is no possibility of ambiguity; when necessary, ordinary brackets (), square brackets [], and braces { } may be employed to obtain clearness.

Tables of Symbols Proposed—I. Quantities

Name of Quantity	Symbol	Symbol recommended for the case in which the principal symbol is unsuitable
1. Length	l	In dimensional equations the capital letters L, M, T, are to be employed.
2. Mass	m	
3. Time	t	
4. Angles	$\alpha, \beta, \gamma \ldots$	
5. Acceleration of gravity	g	
6. Work	A	W
7. Energy	W	U
8. Power*	P	*
9. Efficiency	η	
10. Number of turns in unit of time	n	
11. Temperature centigrade	t	θ ϑ
12. Temperature absolute	T	Θ
13. Period	T	
14. Angular frequency $(2\pi/T)$	ω	
15. Frequency	f	ν **
16. Phase displacement	φ	
17. Electromotive force	E	
18. Current	I	
19. Resistance	R	
20. Resistivity	ρ	
21. Conductance	G	†
22. Quantity of electricity	Q	
23. Electrostatic flux-density	D	
24. Capacity	C	
25. Dielectric constant	ϵ	
26. Self-inductance	L	$\mathfrak{L}$ or heavy-faced or special type.
27. Mutual inductance	M	$\mathfrak{M}$ or heavy-faced or special type.
28. Reactance	X	$\mathfrak{X}$
29. Impedance	Z	$\mathfrak{Z}$
30. Reluctance	S	$\mathfrak{R}$ or heavy-faced or special type.
31. Magnetic flux	Φ	$\mathfrak{F}$ or heavy-faced or special type.
32. Magnetic flux-density	B	$\mathfrak{B}$ or heavy-faced or special type.
33. Magnetic field	H	$\mathfrak{H}$ or heavy-faced or special type.
34. Intensity of magnetization	J	$\mathfrak{J}$ or heavy-faced or special type.
35. Permeability	μ	
36. Susceptibility	κ	

* A symbol for "Power," in the second column, is left "with power" to the Austrian and German committees, to be inserted by them.

** This letter ν may be suppressed later at the instance of the Austrian and German committees.

† A symbol for conductance in the second column is left "with power" to the Austrian and German committees, to be inserted by them.

¶ The German delegate makes reservations as to symbols Nos. 13, 14, 20, 23, 25, 27 to 31, which are not yet accepted in Germany, but does not oppose their adoption by the I. E. C.

II. UNITS. SIGNS FOR NAMES OF UNITS

Sign for names of Electrical Units to be used only after numerical values.

Name of Unit	Sign
1. Ampere	A
2. Volt	V
3. Ohm	*
4. Coulomb	C
5. Joule	J
6. Watt	W
7. Farad	F
8. Henry	H
9. Volt-coulomb	VC
10. Watt-hour	Wh
11. Volt-ampere	VA
12. Ampere-hour	Ah
13. Milliampere	mA
14. Kilowatt	kW
15. Kilovolt-ampere	kVA
16. Kilowatt-hour	kWh

m	sign for milli-
k	sign for kilo-
μ	sign for micro- or micr-
M**	sign for mega- or meg-

* One or other of the symbols O and Ω is recommended provisionally to represent the ohm. The symbol Ω should no longer be employed for the megohm.

** Greek capital letter.

III. MATHEMATICAL SYMBOLS AND RULES

Name	Symbol	Symbol recommended for the case in which the principal symbol is unsuitable
Total differential	d	*d*
Partial differential	δ	
Base of Napierian logarithms	e	ε
Imaginary $\sqrt{-1}$	i	j
Ratio of circumference to diameter	π	
Summation	Σ	
Summation, integral	∫	

IV. MISCELLANEOUS ABBREVIATIONS FOR WEIGHTS AND MEASURES.

Length: m; km; dm; cm; mm; μ = 0.001 mm.
Surface: a; ha; m^2; km^2; dm^2; cm^2; mm^2.
Volume: l; hl; dl; cl; ml; m^3; km^3; dm^3; cm^3; mm^3.
Mass: g; t; kg; dg; cg; mg.

Speed Notation

The Special Committee on Symbols refers the question of finding a suitable name for "speed of rotation expressed in revolutions per minute" to the Special Committee on Nomenclature.

The I. E. C. recommends to the International Electrical Congress of San Francisco the adoption of the name "Siemens" for the practical unit of conductance.

APPENDIX B

Limits of Observable Temperatures Adopted by the I. E. C. in September, 1913

Applicable only to windings for rotating machinery, the terminal pressures of which do not exceed 4000 volts, and to dry transformers with solidly impregnated coils up to 10,000 volts.

Non-impregnated cotton	80 deg. cent.
Impregnated cotton or paper—general	90 " "
" " single-layer field coils, stationary or moving)	95 " "
" " stationary coils solidly impregnated throughout	95 " "
" " Rotor and stator windings having the slot portion solidly impregnated or molded	95 " "
Enameled wire (without cotton)	105 " "
Mica, micanite, asbestos—general	115 " "
" " single-layer field-coils, stationary or moving	120 " "
" " stationary coils solidly impregnated or moulded	120 " "
Windings permanently short-circuited.	
Insulated	100 " "
Non-insulated	110 " "
Commutators—slip rings	90 " "
Bearings	80 " "

The temperature limits for oil-immersed transformers were not assigned.

APPENDIX C

Translation from the French text adopted at Berlin on the *Annealed Copper Standard.*

Report of the National Laboratories Concerning an International Standard for Copper

I. Annealed Copper

The following values should be taken as normal for annealed standard copper.

1. At 20 deg. cent., the resistance of an annealed copper wire 1 meter long and having a uniform cross-section of 1 sq. mm. is 1/58 ohm = 0.017241...ohm.

2. At 20 deg. cent., the density of annealed copper is 8.89 grams per cu. cm.

3. At 20 deg. cent., the coefficient of variation of resistance with temperature of annealed copper, measured between potential terminals rigidly attached to the wire (constant mass), is 0.00393 = 1/254.5 per deg. cent.

4. Consequently, it follows from (1) and (2) that, at 20 deg. cent., the resistance of an annealed copper wire of uniform cross-section 1 meter long and having a mass of 1 gram is (1/58) × 8.89, or 0.15328...ohm.

II. Industrial Copper

1. The conductivity of annealed copper should be expressed at the temperature of 20 deg. cent. in percentage of that of standard annealed copper, and ordinarily to a precision of 0.1 per cent.

2. The percentage conductivity of annealed industrial copper should be computed in accordance with the following rules:

(*a*) The observation temperature should not differ from 20 deg. cent. by more than 10 deg. cent.

(*b*) The resistance of a wire of industrial copper one meter long and of one sq. mm. cross-section, increases 0.000068 ohm per deg. cent.

(*c*) The resistance of a wire of industrial copper one meter long and of one gm. mass, increases 0.00060 ohm per deg. cent.

(*d*) The density of industrial annealed copper at 20 deg. cent. should be taken as 8.89 gm. per cu. cm.

This value of the density should always be employed in the computation of conductivity in percentage of that of the annealed copper standard.

It follows from the above that if R is the resistance in ohms, at t deg. cent. of a wire having a length of l meters and a mass

of m grams, the resistance of a wire of the same copper one meter long and one sq. mm. cross-section will be

$Rm/(l^2 \times 8.89)$ ohms at t deg. cent. and
$Rm/(l^2 \times 8.89) + 0.000068\,(20 - t)$ ohms at 20 deg. cent.

The percentage conductivity of this copper is thus

$$100 \times \frac{0.01724}{\dfrac{Rm}{l^2 \times 8.89} + 0.000068\,(20 - t)}$$

Similarly, the resistance of a wire of the same copper one meter long and one gm. in weight is

Rm/l^2 ohms at t deg. cent., and
$Rm/l^2 + 0.00060\,(20 - t)$ ohms at 20 deg. cent.

The percentage conductivity is thus:

$$100 \times \frac{0.1533}{\dfrac{Rm}{l^2} + 0.00060\,(20 - t)}$$

NOTE 1. The standard values given in (I) are mean values deduced from a large number of tests. Among a number of samples of copper of normal conductivity, the density may differ from normal density up to 0.5 of one per cent, and the temperature coefficient of resistivity may differ from the normal up to one per cent; but between the limits indicated in (II) these deviations will not affect the values of the computed percentage conductivity, if the resulting values are limited to four significant digits.

NOTE 2. The values above stated correspond to the following physical constants for standard annealed copper, all at the temperature of 0 deg. cent.

Density, 8.90 gm. per cu. cm.

Coefficient of linear expansion 0.000017 per deg. cent.

Resistivity, 1.5879* microhm-cm.

Volume resistivity temperature-coefficient 0.00429* per deg. cent. from and at 0 deg. cent.

Resistance temperature coefficient at constant mass, 0.00427 = 1/234.5 per deg. cent. from and at 0 deg. cent.

*These two numerical values will probably be changed to 1.5880 and 0.00428 by the National Physical Laboratories. Since reference is made exclusively to the values at 20 deg. cent. when measuring and stating percentage conductivity, these physical constants for 0 deg. cent. are of secondary importance in engineering.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR FISCAL YEAR ENDING APRIL 30, 1913

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its annual report for the fiscal year ending April 30, 1913.

The report includes abstracts from the reports of the various standing and special committees of the Institute; also detailed financial statements showing the condition of the respective Institute funds, receipts and disbursements, assets and liabilities, and other data.

The Board has held 10 meetings during the year; nine at Institute headquarters in New York, and one in Boston during the Annual Convention in June.

The Annual Convention was held in Boston June 24–28, 1912. The total registered attendance was 936, of which 458 were members of the Institute, and 478 were guests, including 198 ladies. The local attendance was 465, and the attendance from outside of the city of Boston and suburbs was 471. Sixty papers were presented at the technical sessions; one session was held jointly with the Illuminating Engineering Society and one with the Society for the Promotion of Engineering Education.

A Midwinter Convention held at Institute headquarters in New York February 26–28, 1913, under the auspices of the Standards Committee, marked a departure from the usual program of Institute meetings of the convention type, being the first convention to be held in New York since the Institute was organized. The meeting was eminently successful from the standpoint of the results accomplished. The data presented in the various papers and discussions will be of great value to the Standards Committee in formulating its revision of the Standardization Rules. Forty-four papers were presented in brief abstract, and the balance of the time was devoted to the discussion. The registered attendance at the convention was 422, of which 179 were from outside of New York and suburbs. The convention closed with a reception and ball at the Hotel Astor, under the auspices of the New York Reception Committee, which was attended by about 300 members and guests, and which was one of the most enjoyable social functions ever given by the Institute.

An Institute meeting, under the auspices of the Schenectady Section, was held in Schenectady on May 17, 1912. Ten technical papers were presented and discussed. The registered attendance was 354 members and guests.

A two-day Institute meeting was held in Pittsburgh on April 18 and 19, 1913, under the auspices of the Pittsburgh Section and the Committee on the Use of Electricity in Mines. Eight papers were presented, and the total attendance was about 300 members.

Upon the request of the Pacific Coast Sections, the Board of Directors

assigned the Pacific Coast Convention this year to the Vancouver Section, and the date has been set for September 9–11, 1913.

During the year President Mershon visited the following Sections: Ithaca, San Francisco, Los Angeles, Philadelphia, Pittsfield, Pittsburgh and Chicago.

On May 21, 1912, constitutional amendments were adopted creating a third grade of membership. As full information regarding these amendments was given to the membership prior to their adoption, it is not necessary again to go into these details in this report. The effect of the amendments during the year has been the transfer of 389 Associates to the grade of Member, and 308 Members to the grade of Fellow, all under the special section of the Constitution, and 9 Members to the grade of Fellow, under the regular provisions of the Constitution.

The constitutional amendments providing for the appointment of the Secretary by the Board of Directors instead of election by the membership were also adopted on May 21, 1912.

The Committee on Organization of the International Electrical Congress, San Francisco, 1915, consisting of about 200 members located in various parts of this country and abroad, was appointed by the President in June, 1912. The duties of this committee are to organize and carry to a successful conclusion the international electrical congress which is to be held in San Francisco in 1915 during the Panama-Pacific Universal Exposition. A brief report of the committee's progress is included herein.

In June, 1912, the Board of Directors passed resolutions agreeing to participate to a limited extent in the proposed International Engineering Congress, which is also to be held in San Francisco during the Panama-Pacific Exposition. This congress is in charge of a committee of management composed of representatives of the principal American engineering societies. The Institute's participation is, however, limited, owing to its obligations in connection with the electrical congress.

On June 27, 1912, the Board authorized the President to enter into reciprocal visiting member arrangements with certain European engineering societies with which negotiations had been pending with such relations in view. The arrangements entitle members of the American Institute of Electrical Engineers, while abroad, to the privileges of membership in the foreign societies interested in the plan, for a period of three months, and foreign members of these societies visiting this country are entitled to the privileges of Institute membership for a like period. The foreign societies which have entered into these relations with the Institute are: The Institution of Electrical Engineers, of England; the Verband Deutscher Elektrotechniker, of Germany; the Societe Internationale des Electriciens, of France; the Associazione Elettrotecnica Italiana, of Italy; the Association Suisse des Electriciens, of Switzerland; and the Koninklijk Instituut van Ingenieurs, of Holland. A considerable number of foreign engineers and Institute members have availed themselves of these privileges since the arrangements were completed.

Foreign relations have been further strengthened during the year by an arrangement entered into by President Mershon on behalf of the Institute with certain foreign engineering societies to exchange abstracts of the papers presented before the societies, for publication in the official organs of the respective societies. This practise was but recently inaug-

urated, and the first foreign abstracts to be published under this arrangements appeared in the April, 1913, PROCEEDINGS.

Upon the suggestion of President Mershon the Electrophysics Committee arranged with Professor Edwin Plimpton Adams, of Princeton University, for the presentation before the Institute of a series of lectures on the subject of radioactivity. Professor Adams, one of the best known authorities on radioactivity in this country, delivered the lectures during the latter part of March and the early part of April, 1913. The widespread interest manifested in the subject by those who attended prompted the Board to authorize the publication of the entire series in the Institute PROCEEDINGS in order that the entire membership might have this opportunity of obtaining practical and theoretical knowledge of this interesting and important subject. These lectures will also be reprinted in pamphlet form for sale at a nominal price.

Two new technical committees have been created during the year; namely, the Committee on the Use of Electricity in Mines, appointed in December, 1912, and the Committee on the Use of Electricity in Marine Work, appointed in April, 1913, both of which will open to the Institute new and important fields of usefulness and activity.

The following brief statements, consisting principally of abstracts from the reports of various Institute committees, give an outline of the results accomplished. A large amount of work has also been done by temporary committees, appointed during the year for some specific purpose; also by delegates of the Institute to meetings of other technical organizations, and by representatives upon various boards, commissions, and other local and national bodies.

In the limited amount of space available it is not possible to give more than an outline of the activities of the Institute, but this is sufficient to indicate the wide scope, and the constantly increasing amount, of the useful work that is being carried on by the American Institute of Electrical Engineers through its members, committees and officers.

Sections Committee.—In accordance with the custom that has been followed for a number of years, the activities of the Sections and Branches are summarized briefly in tabular form, as follows:

	Year Ending					
	May 1 1908	May 1 1909	May 1 1910	May 1 1911	May 1 1912	May 1 1913
SECTIONS						
Number of Sections	21	24	25	25	28	29
Number of Section meetings held	141	160	187	208	231	244
Total attendance	7,476	16,427	16,694	15,243	19,800	22,825
BRANCHES						
Number of Branches	22	26	31	36	42	47
Number of Branch meetings held	143	198	237	255	281	357
Attendance	4,128	8,443	10,255	10,714	10,255	11,808

No mere table can show the real influence of the Sections of the Institute. In a larger and larger sense the Sections are becoming the Institute. Primarily the Sections are having a nationalizing influence. While it is undoubtedly true that the Sections have tended to reduce general interest in the regular monthly meetings in New York, at the same time an interest in local Section meetings has been stimulated that in the aggregate has made for a vastly increased interest in the Institute. Individual Section meetings are now taking on a character that would have done credit to the general Institute meetings of a few years back. Opportunities which formerly were available only to those so situated that they could attend the New York meetings are now open to those around 29 different centers.

Another gratifying result is the rapid increase in the number of University Branches. The principal benefit that is derived from these Branches is to bring our Institute to the attention of those who in a few years will be ready to take their active part in the electrical engineering profession.

The Sections Committee reports a very satisfactory year.

Committee on Sections Participation in Conduct of Institute Affairs.—The work of this committee is not sufficiently advanced to permit the submission of a complete report, for the reason that not all of the Sections have replied to the communication sent them by the committee, and the committee has not felt itself in a position to formulate conclusions even of a preliminary nature until a fuller response is received from the Sections.

As the resolution under which this committee was appointed was drawn in response to a resolution adopted at the Sections Conference at the Boston Convention in June, 1912, it was the sense of the committee that suggestions or recommendations on the matters coming within its scope should be requested of the Sections. In answer to the committee's invitation for comments replies have been received from about one-third of the Sections. In nearly all of these communications the Sections concerned have brought forward interesting and profitable suggestions relative to the work and activities of the Sections as Sections, but, in the main, no comments have been received indicating a desire for a change from the present system of the conduct of Institute affairs or bearing directly on the question of the participation of the Sections therein.

A formal report will be presented during the Annual Convention.

Meetings and Papers Committee.—During the year the committee has arranged for six regular meetings in New York, a series of five lectures on radioactivity, a midwinter convention, and a meeting at Pittsburgh. It has been the policy of the Meetings and Papers Committee this year to assign each of the regular meetings of the Institute to one of the technical committees, which has obtained the papers and under whose auspices the meeting has been conducted. The chairman of the technical committee supplying the program for any meeting has presided at the technical session of such meeting.

During the present year the 60-day rule in regard to papers has also been adopted, under which every paper to be presented before the Institute must be in the hands of the Meetings and Papers Committee at least 60 days prior to the date of the meeting at which it is to be presented, and no assignment of a paper to any meeting is made until the manuscript is in the committee's hands. The operation of this rule has worked out very successfully, both in permitting the committee to give more con-

sideration to the papers presented and in permitting publication of the papers sufficiently in advance of the meetings to facilitate valuable discussion.

At the 1912 annual convention held in Boston 60 papers were presented, and joint sessions were held with the Society for the Promotion of Engineering Education and the Illuminating Engineering Society. This large number of papers required the holding of parallel sessions each day of the convention and afforded rather limited time for the discussions. Preparations are now under way for the 1913 annual convention to be held in Cooperstown, N. Y., June 23–27, and it is the intention to limit the technical program to 20 or 25 papers. According to the committee's plans, those papers which cannot be included in the convention program will be held over until fall in order to supply the incoming committee with papers for use at the first two or three fall meetings before the new committee has had opportunity to get actively at work.

New York Reception Committee.—The New York Reception Committee has arranged for the smokers which have been held at Institute headquarters in connection with the monthly meetings. These smokers have been supported entirely by voluntary contributions from members residing in and near New York.

The committee arranged for the reception and ball held at the close of the Midwinter Convention in New York in the latter part of February, and maintained in the Engineering Societies Building during the convention a bureau of general information for out-of-town members and guests.

In co-operation with the local committees of the American Society of Mechanical Engineers and the American Institute of Mining Engineers the committee participated in the presentation before the three societies on April 4 of a demonstration of Edison talking moving pictures.

Railway Committee.—The Railway Committee has prepared for presentation at the Annual Meeting in May, 1913, two papers: One on 2400-*Volt Railway Electrification*, by H. M. Hobart, and the other on *Trunk Line Electrification*, by Charles P. Kahler. Invitations for oral and written discussions of these papers, together with printed copies of the papers themselves, have been sent to various members and to foreign engineers interested in railway operation.

Educational Committee.—The Educational Committee, following the suggestion of last year's committee, directed attention again this year to the field of industrial education, and at a meeting of the committee held in January the subject was divided among the members for study and report. The result of the committee's work will be the presentation of a number of papers on various phases of industrial education at the Annual Convention.

On January 10, 1913, the Board of Directors authorized the committee to appoint a representative to attend the first annual convention of the National Association of Corporation Schools, held in New York on January 24. Professor W. I. Slichter was appointed and represented the Institute at the convention. The association is composed of corporations and companies which are engaged in or interested in the education of their employees. Its objects are to collect and compile records of successful and unsuccessful methods of educating employees and to distribute this

information to members of the association. Although it does not seem possible nor at the present time advisable for the Institute to take any official part in the movement, it is believed that the Institute, through the Educational Committee, can assist and thus do a public service by keeping the membership advised of the work of the association.

High-Tension Transmission Committee.—The December, 1912, Institute meeting in New York was held under the auspices of the High-Tension Transmission Committee. At this meeting two papers were presented on the subject of "Testing of High-Tension Line Insulators." The committee has been studying this subject since that meeting, and is preparing for a further discussion at the coming Annual Convention, with the idea of later recommending, if possible, a model or a general specification for the testing of such insulators. The committee has secured two tentative specifications; one representative of the point of view of the manufacturer of insulators; the other the point of view of the scientist and expert tester. It is proposed that the High-Tension Transmission Committee, taking the point of view of the practical engineer, prepare from these a single specification which may be submitted to the Institute for approval.

The committee has prepared and is about to send out a list of questions bearing on engineering matters of special interest in connection with high-tension power transmission systems, to the managers of plants operating at voltages of 25,000 or higher. It is hoped that from the replies to these questions a great deal of valuable information may be gained as to the present practise in such systems. This plan, which is similar to that successfully tried 10 years ago by President Mershon, who was then chairman of the High-Tension Transmission Committee, is now taken up at his suggestion.

It is not expected that either the high-tension testing specification or the collection of engineering data will be completed during the life of the present committee, but it is hoped that the work will be carried on to a successful conclusion by the succeeding committee which takes office on August 1 next.

Electric Lighting Committee.—The Electric Lighting Committee has not held any meetings, owing to the wide geographical distribution of its membership, and the work has therefore been carried on through correspondence. The committee originally arranged for a meeting to be held in February, but it was postponed on account of its proximity to the Midwinter Convention, and no later date could be fixed upon for this meeting. The committee's work has therefore consisted in obtaining papers for presentation before the Annual Convention, and three paper on subjects of timely interest in the electric lighting field have been submitted for this purpose.

Industrial Power Committee.—The Industrial Power Committee has confined its work entirely to arranging for papers and the discussion of these papers at the regular Institute meetings, and in giving assistance and suggestions to Sections regarding papers for Section meetings. In the selection of papers special care has been taken to select papers of general interest which would evoke considerable discussion. The papers arranged for have covered a fairly wide range of subjects so as to make the complete program for the year representative of the variety of problems

encountered in industrial engineering. In addition to papers already presented the committee has provided five papers for the Annual Convention.

Telegraphy and Telephony Committee.—The Telegraphy and Telephony Committee held no meetings during the year, the widely scattered membership of the committee making a full meeting difficult. Arrangements have been perfected which will result in the presentation of a number of papers on telegraphy and telephony at the Annual Convention. There has developed among Institute members a disposition to consult the Telegraphy and Telephony Committee on special problems. None of these has been sufficiently important to require that it be presented to the committee in general, but the tendency is here reported upon as of interest in indicating a new form of usefulness which an Institute committee might develop. The chairman has answered such inquiries to the best of his ability.

Electrochemical Committee.—The work of the Electrochemical Committee for the year has been confined to attempts to secure suitable papers on electrochemical subjects, treated from an engineering viewpoint. Owing to the scattered geographical distribution of its members, no meetings have been held, and the work has been carried on through correspondence. It was decided not to have a meeting devoted to electrochemistry, but to obtain a few papers for the Annual Convention. Two papers have been promised and will be available in time for advance printing.

Power Station Committee.—The Power Station Committee obtained the paper on *High-Speed Turbo-Alternators—Designs and Limitations*, which is believed to be one of the best and most useful papers presented before the Institute during the past year. In addition to this a paper is to be presented under the auspices of this committee at the Annual Convention, on *Standardization of Method for Determining and Comparing Power Costs in Steam Plants*. It is hoped that the latter paper will bring out a discussion that will be of value to the Standards Committee in the revision of the standardization rules, with special reference to a method of determining and comparing costs of power.

Electrophysics Committee.—The efforts of the Electrophysics Committee have been exerted in three directions: 1. To the securing of papers on subjects more particularly pertaining to the physical theory underlying electrical engineering. 2. To the arrangement of a series of lectures on radioactivity. 3. To the stimulation of interest in experimental research.

The Institute meeting in New York on March 14, 1913, was held under the auspices of this committee, and two important papers were presented.

The committee arranged the series of lectures on "Radioactivity" given by Professor Edwin Plimpton Adams of Princeton University, in the latter part of March and early April.

The committee has, through correspondence, made several efforts to secure a list of subjects for research and of questions whose answers are needed in the pursuit of various branches of the profession. So far the results from these attempts have not been numerous, but it is believed that such results could not be expected to follow immediately, and it is hoped

that the succeeding committee will find that a promising start has been made in this direction.

Committee on the Use of Electricity in Mines.—The Committee on the Use of Electricity in Mines, in co-operation with the Pittsburgh Section, held a very successful meeting in Pittsburgh on April 18 and 19, devoted largely to the subject of central station power for mining purposes. The attendance at the meeting was about 300, and there was a good general discussion of the papers presented. Following this meeting the committee held an informal session at which it was decided to co-operate with the Pittsburgh, Chicago and Philadelphia Sections in the preparation of papers pertaining to electrical mining, and to assist in bringing out a full discussion. Nothing further is contemplated at the present time except that the committee will tabulate a list of electrical mining men who might be interested in the activities of the Institute, with the view to communicating with them through the various Sections, and if possible enlisting them in the work. This phase of the work will be undertaken by the Sections themselves with the co-operation of the Membership Committee.

Editing Committee.—Twelve numbers of the PROCEEDINGS have been published under the auspices of the Editing Committee since April 30, 1912, the total number of pages published during this period being 3460, of which 473 pages comprise Section I, and 2987 pages Section II. Owing to the increasing amount of material to be published in our TRANSACTIONS, the Editing Committee determined to reduce the bulk and cost of the volumes by printing the TRANSACTIONS on a thinner paper of better quality, which will permit the publishing of the volume for 1912 in two parts, although it contains approximately the same number of pages for which three parts were required the previous year, printed on the heavier paper. All of the discussions at the regular Institute meetings and at the Sections which have been printed have been edited and published under the supervision of the Editing Committee.

Indexing Transactions Committee.—The Indexing Transactions Committee has completed the work of classifying the synopses of the papers and the arranging and editing of the cards. At the present time the whole manuscript for the two volumes of the index (one covering the period 1884 to 1900, and the other 1901 to 1910 inclusive) is on the press.

Standards Committee.—The Standards Committee has under consideration a revision of the Standardization Rules, and has appointed a subcommittee to collect material for such revision. It was considered desirable to present to the Institute, for discussion, papers from engineers in construction and installation, indicating directions in which modifications of the existing rules might well be made. The Board of Directors authorized on August 8, 1912, the holding of a Midwinter Convention in New York. This convention was assigned by the Meetings and Papers Committee to be held on February 26, 27 and 28, 1913, under the auspices of the Standards Committee. Forty-four papers were prepared for this convention, forty-two of which were printed in advance in the February PROCEEDINGS, and two in the March PROCEEDINGS. Herr Leo Schüler attended the convention as a delegate from the Verband Deutscher Elektrotechniker.

In November, 1912, the American Society of Mechanical Engineers appointed a special committee to confer with the Standards Committee, and a joint meeting of the two committees was held on December 13, 1912, with Mr. H. G. Stott of the A. S. M. E. committee as chairman. Certain resolutions were passed by the joint committees in favor of the adoption of the "myriawatt" as a unit of power. The report of this joint meeting appears on pages 59 and 60 of the February, 1913, PROCEEDINGS. The report received the approval of the governing boards of both societies.

Meetings of the committee have been held at monthly intervals during the year, except during June, July and August.

Reciprocal relations have been entered into to some extent between this committee and the standards committees of the A. S. M. E., the A. S. F. T. M., and the I. E. S., under a resolution on the subject adopted by the Board of Directors on April 9, 1913.

Code Committee.—The work of the Code Committee for the year 1912–1913 has been accomplished without a general meeting of the whole committee, the matters coming before it being of such a nature as to permit their disposal by correspondence.

The important work of the Code Committee really consisted in its representation at the biennial meeting of the National Board of Fire Underwriters, in order to assist in presenting data for the purpose of making the mandatory grounding of secondaries an accepted rule by the Board of Fire Underwriters. The chairman of the committee attended the four-day conference held in New York on March 24–27, and reports that the mandatory grounding of secondaries up to 150 volts, and the permissible grounding of secondaries up to 250 volts, has been approved by the National Board of Fire Underwriters, and the mandatory rule will be printed in the 1913 code.

Law Committee.—The Law Committee, in its advisory capacity, has during the year presented its views upon the following questions which have been submitted to it: The question as to the date upon which the total membership of the Institute should be taken in estimating the number of ballots required to adopt amendments; amendments to the By-laws with reference to the question of transfers under the special section of the Constitution; interpretation of the Constitution and By-laws with reference to certifications under the special section, including a proposed amendment to the special section of the By-laws; modification of the Wheeler Deed of Gift to the Institute library; report on the status of the Secretary of the Institute after August 1, 1912; the question as to the power of the Board of Directors to refuse to transfer applicants under the special section of the Constitution; the form of election ballot to be printed.

Library Committee.—In accordance with Section 24 of the By-Laws of the Institute, we beg leave to submit herewith our annual report for the year ending April 30, 1913, showing the state of the library and including the names of all donors to it.

During the year the erection of two ornamental metal book-cases, one on each side of the main entrance to the library on the 13th floor, has been completed. These are intended to serve for storage and display of a large portion of the Latimer-Clark collection of books which was donated to the Institute by Dr. Schuyler Skaats Wheeler.

As a result of the combined efforts of the Library Committees of the three founder societies, and of the Joint Conference Committee, an organization for the administration of the library by a library board subject to the direction of the Board of Trustees of the United Engineering Society, has been effected, with the approval of the Boards of Directors of these founder societies. The character of the organization is set forth in the following extract from the By-Laws of the United Engineering Society, which went into effect in November, 1912.

LIBRARY AND EDUCATIONAL WORK

74. The Board of Trustees shall maintain and conduct a Free Public Engineering Library, subject to such regulations as it may from time to time determine.

75. The library shall be conducted by a Library Board, subject to the direction of the Board of Trustees.

76. The Library Board shall consist of sixteen members, composed as follows:

Four members designated by each of the three Founder Societies.

The Secretary of each of the three Founder Societies.

The Librarian, who shall also be the Secretary of the Board.

One member shall be designated by each Founder Society each year to serve four years.

Any vacancy occurring among the appointed members shall be filled by the corresponding Founder Society for the unexpired term.

77. Regular meetings of the Library Board shall be held on the first Thursday of February, May, September and December of each year. Special meetings may be called at the option of the Chairman, on not less than seven days' notice, and must be called by the Chairman on the written request of seven or more members. A quorum shall consist of not less than seven members, of whom at least four shall be appointed members, including at least one such member from each of the Founder Societies.

78. At its first regular meeting in each calendar year the Library Board shall elect one of its members to be Chairman for a period of one year or until his successor is elected. At the same meeting the Library Board shall elect from its own members an Executive Committee to consist of an equal number of members from each of the Founder Societies, to serve for one year. The Chairman of the Library Board shall be ex-officio a member and Chairman of the Executive Committee. The Librarian shall be ex-officio Secretary of the Executive Committee, but shall have no vote.

79. If less than a quorum be present at a meeting of the Library Board the members present may adjourn the meeting to a day fixed.

80. The Library Board shall have authority

To originate, revise and approve rules for the administration of the library.

To prepare and forward to the Board of Trustees, requisitions for furniture and other supplies.

To appoint and fix salaries of employees in the library, subject to the approval of the Board of Trustees.

To revise and approve lists of publications authorized by the Founder Societies for purchase, with a view of avoiding unnecessary duplication.

To direct the purchase on account of the UNITED ENGINEERING SOCIETY of publications not on file in the library, under such regulations and within such limits as the Board of Trustees may prescribe.

To receive and administer bequests and gifts to the LIBRARY OF THE UNITED ENGINEERING SOCIETY.

81. At the end of each calendar year the Library Board shall present, to the Board of Trustees and to the Founder Societies, a full report of its acts during the past year, including a financial statement of its receipts and disbursements and its recommendations for the coming year as to policy and finance. This report shall state the recommendation of the Library Board as to the sum of money which each Founder Society should expend during the coming year for the purchase of books for the library of that society; and as to the sum which the United Engineering Society should expend for the purchase of books or periodicals for the Library of the United Engineering Society; and as to the sum each society should contribute toward the cost of administration.

82. A regular meeting of the Executive Committee shall be held on the first Wednesday of each month except July and August. Special meetings may be called by the Chair-

man. A majority of the members shall constitute a quorum, but a less number than a quorum may adjourn the meeting to a day fixed. The Secretary of any of the Founder Societies may be present at any meeting and shall have the same right as members to be heard, but shall have no vote. Notice of each called and adjourned meeting shall be sent to each such Secretary.

83. The Executive Committee shall be the representative of the Library Board and shall execute the instructions of the Library Board, and whenever necessary shall take any action (or which the Library Board has authority, reporting such action for approval to the Library Board at the next following meeting of said Board.

84. The Librarian shall be appointed by the Board of Trustees from a list of names submitted by the Library Board.

85. The Librarian shall be the Executive of the Library Board and of its Executive Committee, and, subject to the direction of said Board and Committee, shall have charge of the library.

86. The Librarian shall be a member and the Secretary of the Library Board, and the Secretary, but not a member, of the Executive Committee.

87. At each meeting of the Library Board the Librarian shall submit a written report containing his recommendations for the purchase of books and supplies, and for any changes in service or in the work of the library.

88. The Board of Trustees shall also co-operate with the Founder or Associate Societies in giving public lectures on engineering and scientific subjects and in arranging for the conduct of educational and research work as from time to time may be deemed advisable.

The Library Board was organized on February 6, 1913, with Dr. Leonard Waldo as Chairman.

Statistical information concerning the library and its use during the year, including a list of donors, is given in the following tables:

DONORS

May 1, 1912—April 30, 1913

ADAMS, E. D.	8
AMERICAN ELECTRIC RAILWAY ASSOCIATION	4
AMERICAN ELECTROCHEMICAL SOCIETY	1
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	3
AMERICAN JOURNAL OF SCIENCE	2
AMERICAN RAILWAY ASSOCIATION	1
AMERICAN SCHOOL OF CORRESPONDENCE	4
AMERICAN TELEPHONE & TELEGRAPH COMPANY	1
ARNOLD, BION J.	12
MR. BISSING	1
BENEDICT, V. L.	1
P. BLAKISTON'S SON & COMPANY	1
BOSTON TRANSIT COMPANY	1
BOSTON WIRE DEPARTMENT	1
BUCHANAN, J. Y.	2
BYLLESBY, H. M.	1
CALDWELL, EDWARD	1
CARNEGIE INSTITUTION OF WASHINGTON	2
CENTRAL STATION PUBLISHING COMPANY	1
CHANDLER, C. de F.	2
CONGRESO CIENTIFICO	1
CUSHING, H. C.	1
DEPARTMENT OF AGRICULTURE	1
DEPARTMENT OF LABOR	2
DEPARTMENT OF TERRESTRIAL MAGNETISM	2
DUNOD & PINAT, PARIS	1
EICKEL, E.	1

ELECTRICAL RAILWAY JOURNAL	1
ENGINEERING NEWS COMPANY	7
FORTSCHRITTE DER PHYSIK	1
FOWLE, F. F	5
GATI, M. B	1
GAUTHIER, VILLARS	3
GEROSA, E	1
HANSEN, L	1
HEIMAN S. & SOHN	1
HERING	1
HERMAN ET FILS, A	2
HOLMGREN, T	2
INDIA RUBBER JOURNAL COMPANY	1
INSTITUTION OF ENGINEERS AND SHIPBUILDERS, SCOTLAND	1
INTERNATIONAL ELECTRIC PROTECTION COMPANY	1
INTERNATIONAL ELECTRICAL CONGRESS, ST. LOUIS	1
IOWA ELECTRICAL ASSOCIATION	1
IOWA ENGINEERING SOCIETY	1
ISOLATED PLANT PUBLISHING COMPANY	1
KANSAS, GAS WATER AND STREET RAILWAY ASSOCIATION	1
KENNELLY, A. E	6
KAHN, H. R	1
LAUFFER, C. A	1
LIBRARY OF CONGRESS	1
LIPPINCOTT COMPANY	2
LOUBAT & CIE	1
MACMILLAN COMPANY	2
MAILLOUX, C. O	1
MARTIN, T. C	10
MARYLAND PUBLIC SERVICE COMMISSION	1
MASSACHUSETTS GAS & ELECTRIC LIGHT ASSOCIATION	1
MASSACHUSETTS INSTITUTE TECHNOLOGY	1
MAVER, WILLIAM, JR	6
MCALLISTER, A. S	1
MCGRAW-HILL BOOK COMPANY	2
MCPHERSON, L. G	1
MERSHON, RALPH D	1
MOIS SCIENTIFIQUE ET INDUSTRIAL	1
MOURLON, CHAS	1
MUNICIPAL ENGINEERING COMPANY	1
MURALT & COMPANY	1
NACHOD SIGNAL COMPANY	1
NATIONAL ELECTRIC LIGHT ASSOCIATION	3
NATIONAL BOARD OF FIRE UNDERWRITERS	1
NATIONAL CIVIC FEDERATION	1
NATIONAL ELECTRIC LIGHT COMPANY	1
NATIONAL FIRE PROTECTION ASSOCIATION	4
NATIONAL WATERWAYS COMMISSION	1
NEW ENGLAND WATER WORKS ASSOCIATION	2
NEW JERSEY BOARD RAILROAD COMMISSION	2
NEW ORLEANS SEWERAGE AND WATER BOARD	1

NEW YORK BOARD OF FIRE UNDERWRITERS	1
NEW YORK BOARD OF WATER SUPPLY	1
NEW YORK ELECTRICAL SOCIETY	1
NEW YORK STATE DEPARTMENT OF LABOR	3
NEW YORK STATE PUBLIC SERVICE COMMISSION	3
NOEGGERATH, J. E	1
NORTH EAST COAST INSTITUTION OF ENGINEERS AND SHIP-BUILDERS	1
NORTH EAST COAST POWER SYSTEM COMPANY	1
OSTERREICHISCHER BETON VEREIN	1
OURO PRETO SCHOOL OF MINES	9
PAINT MANUFACTURERS ASSOCIATION OF THE U. S.	1
PHILADELPHIA DEPT. OF PUBLIC WORKS	1
PIERCE, A. L	2
PLATTHER, WM	1
POLYTECHNIC INSTITUTE OF BROOKLYN	1
PRADO, H. C	1
RAILWAY AGE GAZETTE	1
RAILWAY SIGNAL ASSOCIATION	1
RENSSELAER POLYTECHNIC INSTITUTE	1
SCHOEN, A. M	1
SCOTT, FORESMAN & COMPANY	1
SEVER, G. F	1
SIEMEN & HALSKE	1
SOCIETY OF CHEMICAL INDUSTRY	2
SOCIETY FOR THE PROMOTION OF ENGINEERING EDUCATION	1
SOUTH WALES INSTITUTE OF ENGINEERS	1
SOUTHWESTERN ELECTRICAL & GAS ASSOCIATION	4
SPERRY, E. A	1
TELEPHONE PIONEERS OF AMERICA	1
THOMPSON, SLASON	1
TRANSVAAL INSTITUTION OF MECHANICAL ENGINEERS	1
TREASURY CONSTRUCTION SOCIETY	1
U. S. BUREAU OF STANDARDS	2
U. S. NATIONAL MUSEUM	1
U. S. WAR DEPARTMENT	2
UNIVERSITY OF LONDON PRESS	1
UNIVERSITY OF MINNESOTA	1
UNIVERSITY OF PITTSBURGH	1
VAN NOSTRAND, D. COMPANY	6
WARE, H. E	1
WEAVER, W. D	2
WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY	1
WHITEHEAD, J. B	2
WILEY, J. & SONS	1
ZEHNDER L	4
ZEITSCHRIFT FUR BELEUCHTUNGSWESEN	1
DONOR UNKNOWN	4
OLD MATERIAL	26
	258

Exchanges	172	
Purchases and old material accessioned	399	
		571
Total accessions		829

The following tabulation gives the state of the accounts from which the Library Committee is entitled to draw:

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1912	$271.15		
Interest	6.80	Unexpended	$277.95
	$277.95		$277.95

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications)

Balance May 1, 1912	$78.55	Expended	$46.00
Interest	45.00	Unexpended	77.55
	$123.55		$123.55

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904, FUND

(Proceeds available for the purchase of non-American international electrical literature)

Invested in New York City 4½% Bonds	$2268.00
Additions to the Fund	76.85
Total Fund	$2344.85

Balance on hand May 1, 1912	$309.12	Expended	$3.88
Interest	90.00	Unexpended	$395.24
	$399.12		$399.12

WEAVER DONATION

(Available for the purchase of early electrical literature)

Balance May 1, 1912	$6.69	Unexpended	$6.69

INSTITUTE APPROPRIATION ACCOUNT

Appropriation for the year	$4500.00	Salary (one-third) of librarian, assistants, cataloguer and desk attendant, May 1, 1912 to May 1, 1913	$2704.93
		One-third running expenses of library, May 1, 1912 to May 1, 1913	153.76
		Books	1105.44
		Subscriptions	151.63
		Insurance	71.48
		Binding	352.46
		Miscellaneous	18.08
			$4557.78

STATISTICS OF LIBRARY MAY 1, 1913.

Source	Volumes	Pamphlets	Valuation
Report of May 1, 1913	16,141	1512	$32,660
Purchase	357	16	1,051.75
Gifts and exchanges	327	112	682.00
Old material accessioned	14	12	31.00
Unknown	4		8.00
	16,843	1652	$34,432.75

In the following table are given the figures for the total valuation of the Library property:

Books	$34,432.75
Stacks	1,761.05
Furniture, catalogues, cases, etc.	376.00
	$36,569.80

LIBRARY ATTENDANCE

	Day	Night	Total
May, 1912	641	269	910
June, "	519	213	732
July, "	638	closed	638
August, "	561	"	561
September, "	585	146	731
October, "	566	204	770
November, "	669	215	884
December, "	713	214	927
January 1913	640	247	887
February "	674	232	906
March, "	655	275	930
April, "	806	265	1071
Total May 1912-April 1913	7667	2280	9947
Total May 1911-April 1912	8601	2747	11348

The income from the C. O. Mailloux Fund, amounting to $1000, has again been used to maintain the four important sets which were presented to the library by Mr. Mailloux.

Respectfully submitted,

FREDERICK BEDELL
PHILANDER BETTS
DUGALD C. JACKSON
MALCOLM MAC LAREN
SAMUEL SHELDON, *chairman.*

Public Policy Committee.—The Public Policy Committee has not been called upon, up to the present time, to initiate policies, but has acted in a consulting capacity, considering only such matters as have been referred to it by the proper authorities from time to time.

During the past year the committee has held four meetings, at which the following matters have been considered and reports made thereon: Desirability of opposing injurious legislation regarding the American

patent system; proper attitude of Institute Sections towards local civic matters; invitation from Secretary of the Interior Fisher to attend a conference at Washington between government officials and California representatives to consider proper governmental restrictions on hydro-electric developments wholly or partly on land in federal reservations; form of credentials for Institute delegates to other bodies; desirability of organizing a national electrolysis committee; proposed rules and regulations for service supplied by electric companies; desirability of appointing a delegate to Advisory Board of National Conservation Congress; proposed by-law providing for co-operation of Standards Committee with similar committees of other national organizations; policy of the Institute towards proposed legislation in New York State contemplating the licensing of engineers.

Patent Committee.—The Patent Committee, while it has held no meetings, has kept in touch with the President of the Institute by correspondence and telegraph, and through its efforts has, it is believed, exerted effectual influence in preventing adverse patent legislation at Washington.

There has been considerable discussion regarding the advisability of changing the patent laws of the country, and there was introduced during the last Congress a bill known as the Oldfield Bill, intended to rectify some of the present defects of the Patent Laws, as applied to patents pending in the Patent Office and after they are issued. This bill, while meritorious in many particulars, had certain fundamental weaknesses which, had the bill been passed, would have destroyed many of the advantages which it was intended to secure, and, in addition, would have placed inventors in many respects at a greater disadvantage than they now are.

For this reason it seemed best to the members of the committee to oppose the bill and suggest that an independent, unbiased commission be appointed by the President of the United States to analyze the entire patent situation and make recommendations regarding changes in the patent laws. Accordingly, the committee recommended for passage by the Board of Directors certain resolutions, which had been suggested by President Mershon, urging the Congress of the United States to provide for such a commission, and to hold in abeyance all proposed legislation affecting the patent system until such time as the commission shall have had opportunity to hold hearings and study the situation. These resolutions were adopted by the Board of Directors on November 8, 1912, and copies were forwarded to each senator and representative of the United States who was a member of the Senate or House Committee on Patents.

The President of the Institute and several members of the Patent Committee have been more or less active in the matter, and the chairman has visited Washington once for the purpose of discussing it with friends there. Through the arguments that have been produced before the Oldfield Committee by distinguished inventors and others, and partially through the efforts of the committee, four members of which were present in Washington when the bill was discussed, the Oldfield Bill was withheld for presentation for passage at the last Congress.

It is the opinion of the committee that the efforts of the Institute should be directed towards securing the appointment of a commission, as above suggested, by the President or by Congress, for the purpose of going thoroughly into the entire patent situation, and that if such a commission

cannot be secured, the Institute should take an active part in watching and discussing such patent legislation as may be proposed for enactment by Congress.

Committee on Relations of Consulting Engineers.—The Committee on Relations of Consulting Engineers has given consideration to the question of the practicability of the adoption by the Institute of a schedule of charges for professional services analogous to the schedule of recommended charges which has been adopted by the American Institute of Consulting Engineers, but the complexity of the subject is such that the committee has not felt itself prepared to make a definite recommendation to the Board of Directors.

Constitutional Revision Committee.—The Constitutional Revision Committee was appointed last August to consider whether it would be advisable to revise the existing constitution, and if so, to recommend such changes as the committee deemed expedient and desirable. Early in December the committee issued to the membership, through THE FORUM of the PROCEEDINGS, an explanatory letter inviting comments and suggestions. A copy of this letter was mailed separately to the members of the Board of Directors, the members of all Institute committees, and the officers of the Sections and Branches. This letter resulted in the receipt of many helpful suggestions which have greatly assisted the work of the committee. It is the consensus of opinion that the existing constitution is an exceedingly strong instrument, and the changes recommended by the committee are more in the nature of a readjustment of the various sections, with minor additions and eliminations throughout, rather than a rewriting of the constitution. Certain changes have been necessary on account of inconsistencies with present practise owing to the growth and development of the Institute. As no further revision of the constitution is possible this year, the committee recommends that its report be transmitted by the Board to the succeeding administration, to be submitted to the membership next year, if deemed advisable, in accordance with the constitutional procedure.

U. S. National Committee of International Electrotechnical Commission.—No meeting of the I. E. C. has been held since the Plenary Convention in September, 1911, at Turin. Special international subcommittees have, however, held meetings during the past year; namely, the special committee on symbols; the special committee on the rating of electrical machinery; the special committee on prime movers in connection with electrical machinery. These special committees all met at Zurich in January, 1913. Mr. C. O. Mailloux attended the meetings as the representative of the U. S. National Committee. The special committee on the rating of electrical machinery also met at Paris in May, 1912, and Mr. Mailloux also attended that meeting as our representative. A statement from General Secretary C. le Maistre on the Zurich committee meetings appeared in the PROCEEDINGS of the A. I. E. E. for March, 1913, pp. 76–78.

The following official reports have been issued by the central office in London during the last year:

No. 14. List of Terms and Definitions.

No. 15. Resume of Meeting of Delegates of the Special Committee on Nomenclature held at Paris, March, 1912.

No. 16. Resume of Meeting of Delegates of the Special Committee on Symbols held at Paris, March, 1912.

No. 17. Resume of Meeting of Delegates of the Special Committee on the Rating of Electrical Machinery held at Paris, May, 1912.

No. 18. Third Annual Report to December 31, 1911.

No. 19. Resume of Meeting of Delegates of the Special Committee on Symbols held at Zurich, January, 1913.

No. 20. Resume of Meeting of Delegates of the Special Committee on the Rating of Electrical Machinery held at Zurich, January, 1913.

No. 21. Resume of Meeting of Delegates of the Special Committee on Prime Movers in connection with Electrical Plant, January, 1913.

Monthly meetings of the U. S. National Committee have been held throughout the year except during June, July and August. It has carried on a considerable amount of correspondence with the Central Office and with the Standards Committee of the A. I. E. E.

Committee on Organization of International Electrical Congress, San Francisco, 1915.—This committee was appointed last June, with a membership of over 200 Institute members, many of whom were also affiliated with other societies throughout the United States and abroad. The officers, namely the president, four vice-presidents, the secretary and the treasurer, constitute an Executive Committee of seven members, upon whom the preliminary work of organization has devolved. The Executive Committee has held frequent meetings, and tentative plans for the large features of the Congress have been discussed and in a number of respects have been decided upon. As now contemplated the Congress is to be divided into 12 sections as follows:

1. Generation, Transmission and Distribution.
2. Apparatus Design.
3. Electric Traction and Transportation.
4. Electric Power for Industrial and Domestic Use.
5. Lighting and Illumination.
6. Protective Devices; Transients.
7. Electrochemistry and Electrometallurgy.
8. Telegraphy and Telephony.
9. Electrical Instruments and Electrical Measurements.
10. Economics of Central Stations and Systems.
11. Electrophysics.
12. Miscellaneous.

The Executive Committee has under advisement at the present time questions pertaining to the further organization of the Congress, technical papers, finances, etc. Efforts are being made to co-ordinate the work of the Congress with that of the International Engineering Congress which is to meet in San Francisco two weeks later than the Electrical Congress.

John Fritz Medal.—The John Fritz Medal for 1912 was awarded to Robert Woolston Hunt, "for his contributions to the early development of the Bessemer process." The presentation was made at a special meeting of the four national engineering societies represented upon the John Fritz Medal Board of Award, on December 5, 1912, in the Engineering Societies Building, New York.

Edison Medal.—By the unanimous vote of all the members of the Edison Medal Committee, the fourth Edison Medal was awarded on

December 13, 1912, to Mr. William Stanley, of Great Barrington, Mass., "for meritorious achievement in invention and development of alternating-current systems and apparatus." The presentation will be made during the Annual Convention in June.

Board of Examiners.—The Board of Examiners has held eight meetings during the year. It has considered and referred to the Board of Directors with its recommendations a total of 1455 applications of all classes. A summary of these is as follows:

Recommended for election to the grade of Associate.....	803
Recommended for election to the grade of Member.....	7
Recommended for election to the grade of Fellow.....	1
Not recommended for election to the grade of Associate.	4
Recommended for transfer to the grade of Member.....	34
Recommended for transfer to the grade of Fellow.....	11
Not recommended for transfer to the grade of Member..	2
Not recommended for transfer to the grade of Fellow....	11
Recommended for enrolment as students.....	582
Total.....	1455

Membership.—The net increase in membership for the year was 195. The following table shows the number of members in each grade, the total membership, and the additions and deductions which have been made during the year.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1912	5		724	6730	7459
Additions:					
Elected.....			6	746	
Transferred.....		317	443		
Reinstated.....			4	30	
Deductions:					
Died.....		1	5	24	
Resigned.....			3	134	
Dropped.....			8	416	
Transferred.....			314	446	
Membership, April 30, 1913	5	316	847	6486	7654

Net increase in membership during the year.....195

Deaths.—The following deaths have occurred during the year:

Fellow.—Horatio A. Foster.

Members.—Francis Blake, Philip Diehl, F. B. Herzog, J. A. McCrossan and F. A. Warren.

Associates.—Berthil Anderson, C. C. Badeau, A. W. Ballard, S. B. Charters, Jr., John T. Cowling, H. L. Cummings, Jr., Jos. Le Conte Davis, C. E. De Crow, M. A. Deviny, Albert J. Doty, John W. Early, Harry F. Elden, K. W. Endres, Harold Gay, John F. Hammond, James W.

Johnson, H. A. Knoener, W. P. Mifflin, Robert C. Reed, William Schulz, U. E. Taubenheim, H. C. ter Meer, Edward G. Warren and Alfred T. Ziegler.

Total deaths, 30.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

NEW YORK, May 14, 1913.

BOARD OF DIRECTORS,
American Institute of Electrical Engineers.

Gentlemen:

Your Finance Committee respectfully submits the following report for the year ending April 30, 1913.

During the past year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws. Haskins and Sells, chartered accountants, have audited the Institute books and their certification of the Institute finances follows.

In company with your Secretary and a member of the firm of chartered accountants, the committee has examined the securities held by the Institute and find them to be as stated in the accountants' report.

It will be noted that there is a deficit of $11,630.38 for the fiscal year. This has been caused principally by the unusual number of Institute meetings and conventions held throughout the country, and the unprecedented number of technical papers and discussions presented at these meetings, resulting in a corresponding increase in the amount of printed matter distributed to the membership in the monthly PROCEEDINGS and annual TRANSACTIONS.

The expense of printing the papers presented at the Annual Convention of June, 1912, and the Midwinter Convention held in New York in February, 1913, as well as other Institute meetings held late in the spring of 1912, has been concentrated in this fiscal year, resulting in an expenditure on account of the Meetings and Papers Committee this year of $11,650.32 more than during the preceding year, which is almost exactly the amount of the deficit.

This will tend to adjust itself during the next fiscal year, because the holding of the additional Midwinter Convention, the principal expenses of which have already been paid, will enable the Meetings and Papers Committee to reduce to some extent the publishing expenses of the coming Annual Convention.

This, together with the increase in dues for the new grade of Fellow, plus that of the large number of Associates transferred to the grade of Member, will, it is believed, result in the expenditures of the coming year being well within the income of the Institute.

Respectfully submitted,

CHARLES W. STONE,
Chairman, Finance Committee.

NEW YORK, May 12, 1913.

American Institute of Electrical Engineers,
33 West 39th Street, New York.

Dear Sirs:

Pursuant to engagement, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1913, and submit herewith our certificate and the following described exhibits:

EXHIBIT

"A"—General Balance Sheet—April 30, 1913.

"B"—Statement of Cash Receipts and Disbursements for the Year Ended April 30, 1913.

"C"—Statement of Cash Receipts and Donations for Designated Purposes. Also Disbursements, for the Year Ended April 30, 1913.

Yours truly,
(Signed) HASKINS & SELLS
Certified Public Accountants.

CERTIFICATE

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1913, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly sets forth the financial condition of the Institute on April 30, 1913, that the Statements of Cash Receipts and Disbursements are correct, and that the books of the Institute are in agreement therewith.

(Signed) HASKINS & SELLS
Certified Public Accountants.

New York,
May 12, 1913.

AMERICAN INSTITUTE OF

GENERAL BALANCE SHEET

EXHIBIT A.

ASSETS.

LAND AND BUILDING:			
Interest in Engineering Societies Building, (25 to 33 West 39th Street)		$353,346.61	
One-third Cost of Land (25 to 33 West 39th Street)		180,000.00	
Total Land and Building			$533,346.61
EQUIPMENT:			
Library—Volumes and Fixtures		$33,996.36	
Works of Art, Paintings, etc		2,656.35	
Office Furniture and Fixtures		10,922.33	
Total Equipment			47,575.04
INVESTMENTS:			
Bonds:			
New York City, 4½%, 1917, Par $8,000.00.			
New York City, 4½%, 1957, Par $22,000.00		$31,952.50	
City of Wilmington, Delaware, 4½%, 1934, Par $15,000.00		15,997.50	
Chicago, Burlington & Quincy Railroad Company, 4%, 1958, Par $15,000.00		14,606.25	
Stock—Westinghouse Electric & Manufacturing Company, Par $50.00		50.00	
Total Investments			62,606.25
INVENTORY—BOOKS ENTITLED "TRANSACTIONS"			7,628.25
BADGES			916.80
CURRENT ASSETS:			
Cash in Bank		$2,573.09	
Secretary's Petty Cash Fund		1,250.00	
Accounts Receivable:			
Members, for Past Dues		7,175.00	
Advertisers		1,428.00	
Miscellaneous		691.54	
Interest Accrued—Investments		831.25	
Interest Accrued—Bank Balances		86.68	
Total Current Assets			14,035.56
FUNDS—(See Contra):			
Land, Building, and Endowment Fund:			
Cash	$7,115.32		
Interest Accrued	73.41		
		$7,188.73	
Life Membership Fund:			
Cash	$5,525.87		
Interest Accrued	40.00		
		5,565.87	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$472.09		
New York City Bonds, 4½%, 1957, Par $2,000.00	2,268.00		
Interest Accrued	45.00		
		2,785.09	
Mailloux Fund:			
Cash	$77.55		
New York Telephone Company Bond, 4½%, 1939	1,000.00		
Interest Accrued	22.50		
		1,100.05	
General Library Fund:			
Cash	$277.95		
Interest Accrued	2.85		
		280.80	
Weaver Donation—Cash		6.69	
Total Funds			16,927.23
Total			$683,035.74

ELECTRICAL ENGINEERS

April 30, 1913

Liabilities.		
Bond and Mortgage—United Engineering Society—One-third Interest in Land, 25 to 33 West 39th Street		$54,000.00
Current Liabilities:		
Note Payable	$10,000.00	
Accounts Payable—Subject to Approval by the Finance Committee	4,335.91	
Interest Accrued on Mortgage	720.00	
Interest Accrued on Note Payable	131.25	
Total Current Liabilities		15,187.16
Funds—(See Contra):		
Land, Building, and Endowment Fund	$7,188.73	
Life Membership Fund	5,565.87	
General Library Fund	280.80	
Mailloux Fund	1,100.05	
International Electrical Congress of St. Louis—Library Fund	2,785.09	
Weaver Donation	6.09	
Total Funds		16,927.23
Reserve for Depreciation of Furniture and Fixtures		3,737.95
Surplus—Balance, May 1, 1912	$604,813.78	
Less Net Deficit for Year	11,630.38	
		593,183.40
Total		$683,035.74

AMERICAN INSTITUTE OF

STATEMENT OF CASH RECEIPTS AND

ENDED APRIL

EXHIBIT B.

BALANCE MAY 1, 1912:		
General Cash	$9,277.02	
Secretary's Petty Cash Fund	750.00	
		$10,027.02
RECEIPTS:		
Notes Payable—Loan Farmers Loan & Trust Company		$10,000.00
Entrance Fees	$3,885.00	
Current Dues	70,250.25	
Past Dues	4,653.00	
Student's Dues	4,035.00	
Advance Dues	159.00	
Transfer Fees	240.00	
Badges Sold	2,259.00	
		85,481.25
Sales "Transactions," etc.	$1,651.03	
Subscriptions to Proceedings	2,510.80	
Advertising	10,000.26	
Binding	125.00	
Exchange	23.32	
		14,310.41
Italian Memorial Committee		120.00
Interest—Investments	2,626.00	
Interest—on Bank Balances	443.95	
		3,069.95
Total Receipts		$112,981.61
Total		$123,008.63

ELECTRICAL ENGINEERS.

DISBURSEMENTS FOR THE YEAR.

30, 1913

DISBURSEMENTS:

Meetings and Papers Committee:		
Printing Proceedings	11,714.98	
Engravings for "	2,425.21	
Paper and cover stock for Proceedings	7,537.21	
Envelopes for Proceedings	611.37	
Binding and Mailing Proceedings	6,920.41	
Salaries	$3,957.25	
Stationery and Miscellaneous Printing	469.89	
General Expenses	68.75	
Meetings	7,906.78	
Volume No. 30 of Transactions	10,914.71	
Volume No. 31 of Transactions	960.30	
Total Disbursements Meetings and Papers Committee		$53,486.68
Executive Department:		
General Expenses	$2,335.30	
United Engineering Society—Assessments	3,375.00	
Salaries	15,583.75	
Express Charges	230.26	
Postage	3,127.32	
Badges Purchased	2,399.14	
Advertising	1,999.60	
Office Furniture and Fixtures	782.08	
Stationery and Miscellaneous Printing	3,589.46	
Year Book and Catalogue	2,841.57	
Interest on Mortgage	2,160.00	
Total Disbursements Executive Department		38,423.48
Sections Committee:		
Sections Meetings	$3,544.22	
Branch "	189.43	
Delegates to Convention—Traveling Expenses	1,763.64	
Salary and Traveling Expenses—Honorary Secretary	4,345.29	
Salaries, New York Office	2,136.00	
Stationery and Printing—New York Office	659.75	
Express Charges	6.85	
Total Disbursements Sections Committee		12,645.18
Library Committee		4,537.78
Indexing Transactions Committee		1,728.70
International Electrotechnical Commission		36.23
Annual Function		871.00
Finance Committee		150.00
Public Policy Committee		8.50
Standards Committee		7.00
Code Committee		3.50
Code of Principles of Professional Conduct Committee		6.50
Edison Medal Committee		14.25
President's Special Appropriation		424.80
Reception to Honorary Member C. E. L. Brown		106.15
Panama Convention		216.95
Italian Memorial Committee		325.25
Rearrangement of Offices		5,667.56
Special Reception to Foreign Engineers		82.34
Herbert Adams Testimonial		100.00
John Fritz Medal		262.00
E. D. Adams Special Library Fund		61.60
Total Disbursements		$119,185.54

BALANCE, APRIL 30, 1913:

Cash in Bank	$2,573.00	
Secretary's Petty Cash Fund	1,250.00	
		$3,823.00
		$123,008.63

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Cash Receipts and Donations for Designated Purposes. Also Disbursements, for the Year Ended April 30, 1913

Exhibit C.

Receipts and Donations:	
Land, Building and Endowment Fund—Donations, Interest, etc.	$1,807.79
Life Membership Fund	1,178.59
International Electrical Congress of St. Louis Library Fund Donations, and Interest	103.25
Mailloux Fund, Interest	45.00
General Library Fund, Interest	6.80
Total	$3,141.43
Disbursements:	
Life Membership Fund	$480.00
Mailloux Fund	46.00
International Electrical Congress of St. Louis Library Fund	3.88
Total	$529.88

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30	1906	1907	1908	1909	1910	1911	1912	1913
Membership, April 30, each year	3870	4521	5674	6400	6681	7117	7459	7654
Receipts per Member	$12.77	$12.21	$13.01	$13.21	$13.35	$13.37	$13.19	$13.45
Disbursements per Member	10.48	11.62	11.73	10.49	12.03	11.03	12.44	15.57
Credit Balance per Member	$2.29	$.59	$1.28	$2.72	$1.32	$2.34	$.75	*$2.12

* Deficit.

The deficit indicated above was caused principally by the unusual number of meetings held during the past fiscal year, with the consequent increased expenditures for publishing the Proceedings and Transactions, as explained in the Finance Committee's report included herein; by the expense, amounting to $5,667.56, for rearranging the Institute headquarters in order to provide better accommodations for the convenience of out-of-town members; and by an increase of over $3,000.00 in the expenditures on account of the activities of the Sections and Branches.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary*

New York, May 20, 1913.